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# VSTOL AIRCRAFT STABILITY AND CONTROL EXPERIENCE FROM METHODS AND RESULTS OF DO 31 FLIGHT TESTS

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# VSTOL AIRCRAFT STABILITY AND CONTROL EXPERIENCE FROM METHODS AND RESULTS OF DO 31 FLIGHT TESTS

H. Wünnenberg

ABSTRACT: The problems of stability and control are very important for the layout and the operation of V/STOL aircraft. Though the V/STOL Handling Qualities Criteria according to AGARD-Rep. 577 and US-MIL-F-83300 correspond to a certain extent to the flight test results of the Do 31, it has to be said that especially the MIL-Spec. is not reasonably applicable to jet lift V/STOL aircraft with attitude stabilization systems. Even for the AGARD-Rep. 577, some additions seem to be necessary in order to include the special problems of this category of V/STOL-aircraft.

The principles of control and stabilization, which are realized in the Do 31, have proved their validity and have even enabled the pilots to perform simulated IFR transitions up to hovering flight. Nevertheless for an operational aircraft, in order to simplify the handling and for further automation of the landing approach a number of improvements are necessary for all weather operations.

## I. THE MOST IMPORTANT RESULTS FROM DO 31 FLIGHT TESTING AND THEIR IMPORTANCE FOR VTOL TECHNOLOGY /9*

### 1. Influence of the Stability and Controllability Problems on the Design and Operation of VTOL Aircraft

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* Numbers in the margin indicate pagination of original foreign text.

The flight properties of an aircraft, that is, the requirement for stability and controlability, usually influence primarily the design of the control surfaces, the elevators, the control system and possibly the flight controller. They play a subordinate role in a selection of the configuration, which is essentially determined by the performance requirements. This situation is somewhat different for VTOL aircraft, because here the flight property problems determine the overall design and configuration.

The following main points may be mentioned:

- Problems of trimming capability in the case of an engine failure, or by jet induced flow when the flight velocity increases or when there is a ground effect, lead to the specification of the engine configuration.

- The requirements for the control accelerations for trimming and maneuvering influence the magnitude of the installed thrust and the design of the control principles.

- The time variation of the control system also greatly influences the selection of the control principles. For example, this determines whether the control is to be carried out by means of bleed air, jet rudders, by turning the engines or engine nozzles, or if the engine thrust is to be influenced directly. /10

In addition to these aspects which influence the total configuration, the flight handling properties will specify the characteristic data of the control system, such as for example the deflections, linearity, dead times, response threshold, control forces and gradients, couplings and redundancy. The same is true for the design of the flight controller. Therefore, a large number of requirements and directives must be satisfied in order to provide reasonable flight properties for the design of a VTOL aircraft.

The stability and controllability characteristics also greatly influence the operation of a VTOL aircraft. For example:

- Restriction to optimum performance measures because of pilot stress.
- Restriction of free parameters because of controllability during the testing of transition technologies, for example, longitudinal inclination angle and attitude angle.
- Specification of the landing method for side winds or when there is a ground effect.
- Specification of the method of trajectory control during landing approaches.

National and international committees very early developed recommendations and directives in collaboration with research institutes and manufacturers, which will give directives for future developments. The best known recommendations are the following: /11

| | |
|---|---|
| AGARD-Rep. No. 408 | Date of issue Oct. 1962 |
| AGARD-Rep. No. 408 A | Date of issue Oct. 1964 |
| AGARD-Rep. No. 577 | Date of issue Dec. 1970 |
| USAF-MIL-F-83300 with a few preliminary reports | Date of issue Dec. 1970 |

The basis of the recommendations were first extensive simulator studies and flight test results of helicopters. However, these could only be taken over in a very incomplete fashion for true VSTOL aircraft, particularly if they had jet propulsion. In the meantime, a large number of information has been obtained from flight tests with VTOL aircraft. This was especially collected by the AGARD and was published in AGARD Report No. 577. Nevertheless, there still remains certain restrictions for applications of the recommendations to jet support a VTOL aircraft having an attitude (or turning) control system.

## 2. Short Summary of the Most Important Flight Mechanical Results from the Do 31 Flight Test

The Do 31 is a jet supported VTOL transport aircraft. The lifting engines and drive engines are separate. The drive engine thrust is deflected by means of rotatable nozzles in order to support the lift during hovering flight and in order to accelerate and brake during transition. The pitch axis is controlled around the roll axis by means of bleed air from the drive engines and the elevator is moved at the same time. This is done by changing the thrust in the lifting engine gondolas in opposite directions while moving the tail rudder at the same time. Control around the yaw axis is provided by deflecting the lifting engine nozzles in opposite directions and moving the tail rudder at the same time. The stabilization around the pitch axis and roll axis is done by means of attitude control. The stabilization around the yaw axis is done by means of turn control. /12

- Except for true vertical takeoff which requires rapid control measures by the pilot in order to avoid recirculation, the takeoff transition is easy to fly. On the other hand, during landing transition there is an increased pilot stress because of the many configuration changes and the additional navigational stresses.

- The control system used has proven itself. The idea of having no velocity-proportional fade-out was found to be reasonable and correct.

- During transition there is a large pitch trim moment which depends on the flight velocity. For unfavorable conditions it can have the magnitude of the pitch control capacity. The main reason for this is that there is a pitch moment induced by the engine jets in addition to the normal aerodynamic pitch moment which depends on angle of attack. The problem can be avoided by not using large negative angles of attack.

- The control accelerations required for normal maneuvering are considerably smaller when attitude stabilization is used than for manual control.

- The statistical average values of the control accelerations are small for normal maneuvering. For sudden, large control deflections of the Do 31 controller, which operates in the linear range and which uses electrical actuators, there are large control acceleration peaks. /13

- By often moving the rudders during transition, there is a considerable change in the circular amplification in the controller as the flight velocity is increased. It was difficult and took a great deal of time to find suitable fixed controller settings in order to have sufficient transient behavior during hovering flight but to also have no overrun of the attitude at the end of transition or any actuator oscillations (wear of the mechanical linkages). The problem was reduced by means of an adaptive controller.

- The time variation of the individual control axes is different. There are only small time constants in the pitch axis and yaw axis. The pilot was able to fly both axes without stabilization. Because of the lifting engine time constants, there is a delayed time effect for the roll axis so that it is impossible to manually fly this axis without using additional installed roll damper.

- The flight trajectory is controlled especially during landing transition at high flight velocities by changing the pitch attitude. In the low velocity range, this is done by means of a lifting engine thrust. Even though the pilots evaluated the flight trajectory controllability to be satisfactory, it would be desirable to increase the vertical acceleration capacity and to reduce the coupling with the horizontal axis. Both things can be brought about by a type of direct lift control or sinking velocity control. The time variation will be especially important here. /14

- Even though the transition times are relatively short because of the large acceleration and delay values, it was not possible to exploit the optimum possibilities of the Do 31 because of the stresses of the pilot when operating the multi-lever control unit. An improved control unit would be advantageous for this reason.

- The unstable roll behavior for side wind landings or side displacements does not occur in the Do 31, even though it occurs in many VTOL aircraft. During transition, side displacements were compensated for by course changes (rotation into the wind), which was also done to compensate for side wind effects.

- When one engine fails, the controller automatically regulates the attitude changes. The maximum roll attitude perturbation amplitudes evaluated during column experiments amounted to about 5 degrees for a drive engine failure and about 2 degrees for a lifting engine failure. The height loss which occurs depends greatly on the reaction time of the pilot. During the simulations, the average values were between 10 and 20 m.

The main part of the report contains additional information on these points. /15

## 3. Still Unsolved Problems and Possible Development Tendencies for Future VSTOL Aircraft

The flight testing of the Do 31 was carried out without accidents and without serious technical failures. This was only possible because of careful development and tests, which were carried out in steps. These began with model and simulator investigations using test stand flights and free flights with hovering frames. Then conventional flight tests were carried out up to the VTOL tests themselves. However, this does not mean that all problems for the safe and economical deployment of VTOL aircraft have been solved. The flight tests concluded in May, 1970 showed that the Do 31 concept of a V/STOL aircraft can indeed be realized. The first part of the flight tests was used to clarify the most important questions which determine the design, development and operation of a V/STOL transport aircraft with jet propulsion.

Many of the decisive operational problems could only be briefly explored during the first flight testing phase. Some problems were detected as a result of the tests. An additional test phase should be conducted in order to satisfy the environmental problems associated with civilian VSTOL transport aircraft operation; in particular, there is a problem of noise reduction. This will also be required to provide economical and safe all weather operational capability. The yet unsolved problems associated with a V/STOL unit could then be clarified, so that the configuration for a later series production model could be established. Based on the flight experience obtained up to the present, the primary goal of any additional testing would be the improvement of the transition technique in order to provide all weather capability as well as noise and time-optimal flight trajectories. Also the comfort during the controlling process of the aircraft will have to be improved. A number of problems in the area of flight properties must be solved, part of which are important for achieving the overall goals of the project. /16
As an example we have the following items:

- Detailed investigations for the controllability of an engine failure event.
  The control of an engine failure event during all transition phases without any danger is one of the primary problems for civilian use of a V/STOL aircraft. This will be done by designing the best control system and control technique.

- Investigations of curve coordination.
  Because of the interaction between the hovering flight control and stabilization system and the aerodynamic control and stabilization system during transition flight, there are unusual control requirements placed on the part of the pilot. It must be investigated whether these difficulties can be overcome by a partial control technology or by a partial automation.

- Investigations for the improvement of the flight path control.
  When the landing process is automated, it is necessary to have the flight path control without any coupling effects, as much as possible (pitch attitude change, velocity change). This requires the use of a direct lift control. The V/STOL configuration is especially well suited for this.

- Influence of the controller characteristics on the flight properties.
  The pilot evaluation of the flight properties in the transition range depends essentially on the controller characteristics. A correlation with the existing V/STOL flight /17
  property directives must be established. It may be necessary to add to the requirements for flight performance of a jet-supported transport aircraft. This is an important task for the development of future mass-produced aircraft.

- Investigation for the automation of the touchdown process.
  The ground effects (jet interference, recirculation) which occur during vertical landings make the manual control of the touchdown process more difficult. It seems that for civilian applications, it will be necessary to develop a special touchdown automatic system, which will make it

possible to pre-select the touchdown velocity. The corresponding flight mechanical preliminary investigations are necessary.

The Do 31 E3 which is still available could be used as an experimental base for these experiments. Only small modifications would be necessary.

In conclusion we would like to mention the possible development tendencies. The operational aspects of a future V/STOL traffic system are very important. For the flight properties this would mean that the corresponding provisions must be made so that the flight control and control system technologies can be improved, until all weather automatic landing processes have been developed. The Dornier has done some work in this area in collaboration with the DFVLR and the electronic firms ESG and SEL during the years 1970/1971. Such a study was performed at the request of the BMVg (German Defense Ministry) and has the title "All Weather Flight Control Systems for VSTOL Aircraft and Rotary Wing Aircraft" (AFDV). /18

For VSTOL fighter aircraft, the problems of noise abatement and economy are secondary. However, all of the other problems mentioned for transport aircraft also apply for fighter aircraft. /19

## II. STABILITY AND CONTROLLABILITY OF THE DO 31 ACCORDING TO FLIGHT TEST RESULTS

### 1. Introduction

The present report is a summary of the results and data obtained in the area of stability and controllability of jet-supported VTOL aircraft obtained during the Do 31 flight tests. By this we primarily mean the flight properties for hovering flight and transition flight. Only a few special problems are mentioned from the area of conventional flight. These are the results of the VTOL capacity of the aircraft.

Because of the large number of problems associated with the Do 31, only a small part of the total flight program was dedicated to investigating the flight properties. However, a number of basic investigations were carried out during the NASA program, so that we can have essentially a complete picture at this time.

The flight properties of the Do 31 will be very important for the design of future VTOL transport aircraft, because the aircraft is the first jet-supported VTOL aircraft of this size. Therefore valuable material for complementing existing design directives has been obtained. The directives used up to the present, which are the reports [1, 2] offered by NASA in conjunction with the AGARD flight mechanics panel and the specifications [3] developed by the USAF, are essentially based on data for propeller-supported aircraft and helicopters. /20

## 2. The Control System and Stabilization System of the Do 31

Figure 1 shows the principal structure of the control system. The Do 31 is controlled using conventional control organs during the hovering phase. The usual control stick found in transport aircraft is replaced by a short knob installed about in the center of the control column, so that one-hand operation is possible. This is done to improve the visibility conditions and to avoid the danger of injury to the pilot if he is ejected by the pilot ejector seat. One-hand operation is required because especially during landing transition, the pilot requires his other hand for operating the engine levers.

The roll and pitch axes are controlled with the stick. The yaw axis is controlled with pedals. During hovering flight and transition flight, the pitch control moments are produced by lead air taken from the drive engines, which is expelled through two control nozzles attached to the rear end of the fuselage. In addition the elevator is moved in parallel. The roll control moments are produced by the corresponding thrust differentiation in the lifting engine gondolas, and the tail rudder is also moved. The yaw control moments are produced by deflecting the lifting engine nozzles in opposite directions in the gondolas, and the tail rudder is moved at the same time. When transition is made to conventional flight, the VTOL control installation is automatically turned off through the lifting engine thrust lever. The control is then produced by the conventional aerodynamic control surfaces. All of the control moments can be produced by the pilot as well as by the controller.

In addition to the stick and the pedal, the pilot also has two drive engine thrust levers, a lever for controlling the drive engine deflection angle and a lifting engine thrust lever. At the same time, it is used for simultaneously turning on all eight lifting engines (HTW). /21

The block diagrams of Figure 2 show the way the control system operates including the controller. In order to obtain as high initial accelerations as possible and because of safety, the pilot has direct access to the control organs through the linkages. In parallel with this, any stick or pedal displacement represents a controlling variable for the controller. This means that a nominal attitude is commanded by the stick position for the pitch axis and roll axis. For the yaw axis, a pedal position produces a nominal angular velocity. Figure 3 shows the exact correspondence of pedal position and stick position and flight attitude, for the three individual axes. Since the pilot is capable of controlling the pitch axis and the yaw axis in an uncontrolled manner in case of an emergency, but would have considerable difficulty for the roll axis without any stabilization, there is an independent roll damping device for the roll axis which in case of controller failure would make it easier for the pilot to control the roll axis. In order to facilitate the control during landing transition, a pitch attitude pre-selection device is installed for the pitch axis, with which the pilot can pre-select the pitch attitude corresponding to a planned configuration change using a switch. At a suitable time, he can trigger it by means of a pressure switch installed on the control stick.

For conventional flight, there is no artificial stabilization in addition to the roll damping. In order to prevent excessive loads on the aircraft because of control deflections which are too large at high flight velocities, and in order at the same time to reduce the effectiveness of the control organs, which usually rapidly change with stagnation pressure, we installed limitations on the maximum rudder deflections for all three control axes which are proportional to the stagnation pressure. The characteristics are shown in Figure 4.

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## 3. Flight Tests with the Do 31 Carried Out for Determining the Flight Properties

### 3.1. General Remarks

The flight tests started with the controller test frame (small hovering frame). With it, test stand experiments and free flights were used to determine the most important parameters of hovering flight, and the controller was adjusted. After this, we tested conventional flight conditions using the special built version Do 31 E 1. This aircraft corresponded completely to the vertical takeoff aircraft, except for the missing lifting engines, which were replaced by corresponding weights in the gondolas in order to simulate the correct mass ratios. At the same time the E1 tests were going on, we then started the experiments with the so-called "large hovering frame" which already contained an original wing with lifting engines and drive engines, but which only had a temporary fuselage, which, however, corresponded to the original fuselage in the wing area. With this device, we continued the investigation of the hovering flight problems and we again started with the test stand experiments. After the basic data of hovering flight and conventional flight were known, we started with the testing of the vertical takeoff aircraft Do 31 E3 proper. With this aircraft, we primarily investigated problems of transition flight.

Before we give an exact description of the tests carried out to determine the flight properties, we will discuss the methods required for carrying out a typical takeoff and landing experiment.

### 3.2. Sequence of a Typical Vertical Takeoff Process (VTO) /23

The vertical takeoff method is usually a compromise among various problems, which influence the VTO: hot gas recirculation, skidding of the aircraft on the takeoff surface, destruction of the takeoff surface by the engine jets and danger of reingestion of the dispersed particles, pilot stresses and fuel consumption. For the test method of the Do 31, the most important criterion was to avoid the hot gas recirculation. The following sequence was found to be the best possible compromise after several experiments.

Figures 5 a-c show the time variation of the process for a typical test flight. Figure 5 a shows the time variation of the most important flight variables. Figure 5 b shows the variation of the most important pilot activities. Figure 5 c shows a comparison between the pilot activities and the controller activities for controlling and stabilizing the aircraft. The method used can be briefly described as follows:

After the drive engines (MTW) are turned on and run up to an average thrust level, the drive engine nozzles are rotated to 75°. At this point the lifting engines (HTW) are turned on and are run up to "idle". The drive engines are then run up to lift-off thrust, and the aircraft is finally lifted off the ground by running up the lifting engines. The entire process occurs in 35 seconds.

As soon as the undercarriage is unloaded, the controller is turned on automatically. The transition which follows takeoff up to wing-supported flight is relatively easy for the pilot to carry out. As the flight velocity is increased, he slowly turns the drive engine nozzles backwards up to the final position of 10°. Depending on the altitude gain, between 18 and 30 seconds are required for the entire transition.

### 3.3. Sequence of a Typical Vertical Landing Process (VL) /24

During the Do 31 flight tests we were most interested in problems associated with landing transition. We soon found out that the reduction of the pilot effort during this phase represented the main problem of all other possible optimization factors. It is not possible to optimize the fuel consumption by reducing the transition time without changing the actual control system. Therefore, the method to be described below for carrying out vertical landings represents a compromise found after a large number of flight tests between minimum fuel consumption and the smallest possible load on the pilot. The time variation of the most important parameters is shown in Figure 6 a-c in a manner similar to what was shown for the vertical takeoff process. Figure 6 a again shows the most important flight variables. Figure 6 b shows the most important pilot activities and Figure 6 c shows a comparison between pilot activities and controller activities for controlling and stabilizing the aircraft. The details of the process are as follows: first of all the lifting engines are turned on during stationary forward flight. This process lasts about 20 seconds. At a certain point in time, for example, over a landing mark or when the ILS guide beam passes through zero, the descent is introduced by changing the longitudinal inclination, by increasing the lifting engine thrust, and by turning the drive engine nozzles to 120°.

This leads to a delayed descending flight along a straight trajectory. Necessary flight trajectory corrections are carried out by changing the pitch attitude and at low velocities this is done by controlling the lifting engine thrust. The pullout and residual delay is carried out by increasing the longitudinal inclination angle and the lifting engine thrust. The final descent down to vertical landing is controlled using the lifting engine thrust. At the moment of touchdown the controller is automatically turned off. In addition, the lifting engine thrust and the deflection angle of the drive engines must be reversed immediately in order to avoid recirculation. Using this method, /25
the average transition time between turning on the lifting engines and touchdown was between two and three minutes. Further details on the various methods used can be taken from the special report "Transition Techniques".

### 3.4. Experiments during Hovering Flight and on the Test Stand

The test stand experiments were first used to accustom the pilot to the aircraft. They were also used for stimulating dangerous situations. We paid special attention to problems of a drive engine or lifting engine and failure as well as controller failure.

The hovering flights themselves were primarily designed to develop suitable takeoff and landing procedures. Most of the interest centered on the difficulties and problems associated with hot gas recirculation and jet interference. In addition we tested various methods of carrying out translational motions (air taxiing). We investigated the longitudinal direction displacement caused by pitch attitude changes or drive engine deflection angle inputs. We investigated the sideways displacement by letting one wing hang. We investigated ascent and descent maneuvers using drive engine and lifting engine thrust changes. We investigated the rotation around the vertical axis. At the same time we tested transmission and stability behavior by discontinuous inputs to the stick, pedals and engine operational levers. Except for actual takeoff and vertical landing, the hovering flight phase was found to be without problems, so that we only used a relatively small amount of flight time to investigate hovering flight problems.

### 3.5. Experiments During Transitional Flight /26

Most of the flight tests carried out with DO 31 E 3 were addressed to problems of transition flight. The emphasis was on the improvement of the transition techniques, which is discussed in a special report. We also investigated flight properties in the transition range. Except for the usual discontinuous inputs to the actuator organs of the pilot for determining the stability and controllability behavior, a great part of the investigations was devoted to problems of maintaining a specified glide path (ILS guide beam) and to correcting deviations, which represented preliminary investigations of IFR approaches. We used pitch attitude changes, drive engine thrust changes, lifting engine thrust changes, and drive engine deflection angle changes for controlling the glide path. We maintained the glide path at various transition velocities, and from given deviations, we moved back to the guide beam. Sideways corrections caused by letting one wing hang or by course changes were investigated. In addition, we investigated problems of curve coordination, approach with a side wind, influence of turbulence and operational characteristics of the aircraft under IFR conditions.

A large part of the evaluation effort was to determine the required control accelerations and the required trim moments in order to obtain better founded data for new VTOL projects. We also wanted to obtain material for the flight characteristic directives produced within AGARD. /27

### 3.6. Conventional Flight Experiments

Since the flight properties of the Do 31 are hardly different from those of other aircraft for conventional flight conditions, we only carried out the usual experiments in order to test the most important flight property criteria. The slow flight behavior and the stall behavior were investigated. Experiments were carried out with one drive engine off at various deflection angles. We investigated the possibilities of delaying and carrying out steep descents, using the drive engine nozzle displacement. We carried out the usual trimmability and controllability experiments. The dynamic properties were determined for several flight states. Special effort was made in the evaluations to determine the flight mechanical coefficients from the flight test results. Modern statistical methods were used. However, because of the fact that the measurement transducers can only be used in a restricted way for such special evaluations, we only had partial success for the side motions.

## 4. Description of the Evaluation Method /28

### 4.1. Data Preparation

There was a relatively elaborate and convenient measurement installation and data preparation installation available for measuring and storing the data from the experiments. Up to 260 measured values could be stored simultaneously on magnetic tape on board. In addition, a large part of the measured data required for describing the most important flight state variables were directly recorded on the ground using telemetry. These data were also stored on magnetic tape on the ground.

On the data of the 14 channel analog onboard tape was used for the flight mechanical evaluation. These measured values were prepared on the hybrid computer installation depending on the type of commutation and modulation. They were converted to digital form. The interrogation rate was 50 Hz. The data were converted to plots or special evaluation programs were used and special computer tapes. These were applied to the prepared digital flight test tapes, depending on the problem investigated.

### 4.2. Evaluation of the Flight Test Results from Hovering Flights and Transition Flights

### 4.2.1. Manual Evaluation

By "manual evaluation" we refer to the evaluation using measurement recordings, without the use of any other special programs. In order to simplify this rather laborious task, in conjunction with NASA, we prepared a number of plots which gave a certain number of measured values for special time intervals as a function of flight time and which were contained on nine sheets. The measured values shown on one page are related /29 to each other, so that the evaluation is simplified. For example, plots 1 to 3 contain the measurement points required for describing the longitudinal motion, such as stick position, tail nozzle angle, actuator position, longitudinal inclination angle, angular velocity around the transverse axis, height, flight velocity, ascent and descent velocity, angle of attack, acceleration in the x- and z- direction, elevator deflection, trim position and deviation from the guide beam. In addition, there is the possibility of directly having a numerical interpretation of all averaged measured values with an interrogation frequency of 1 Hz, using the so-called "quick looks", which is a list.

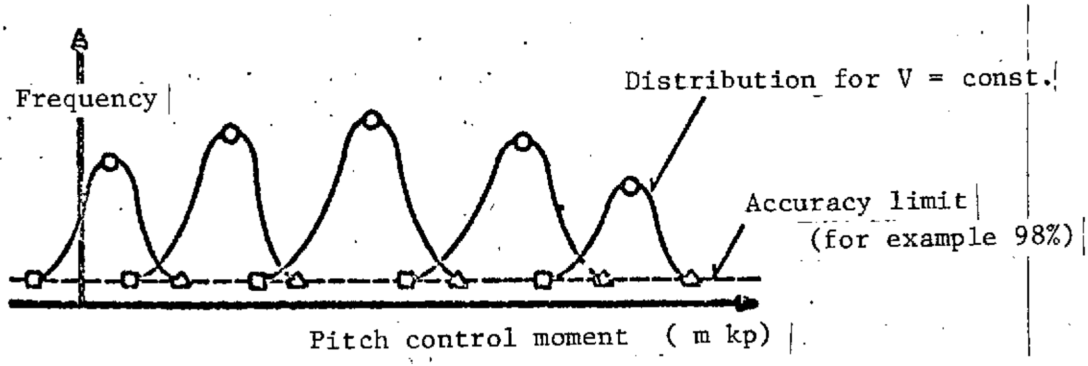
### 4.2.2. Evaluation Programs

Special evaluation programs were developed for the flight mechanical evaluation, some of which are related to each other. There is a program for calculating the actual flight weight, a program for calculating all engine and control thrusts, a program for calculating the exerted control moments and in conjunction with it, a program for calculating the statistical distribution of the control moments. In addition, there is a possibility of making a division into certain velocity classes.

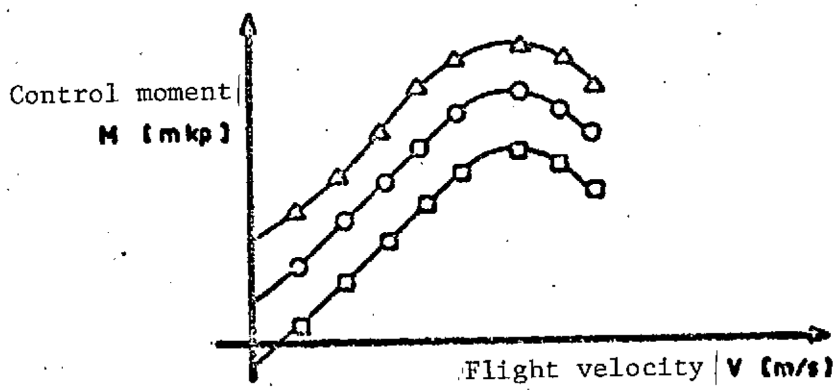
The calculation of the actual flight weights is done by means of an integration of the measured fuel flow rates, starting

with the weighed initial weight. The thrust calculation is usually a difficult problem. For the Do 31, two methods are used for the drive engines and the lifting engines, which are based on test stand data of the engine manufacturer. For the drive engines, the thrusts were first calculated using the rotation rates. They were also calculated using temperature and pressure measurements at the nozzles. For the lifting engines, it was calculated with the rotation rates and with the fuel flow rates. Finally, the thrust in the direction of the thrust /30
vector of the tail control nozzles is done based on the drive engine rotation rate and the nozzle flap angle. After the thrusts are known, one obtains the control moments by multiplying with the corresponding moment arms. The aerodynamic contributions to the control moments which are a consequence of the rudder deflections are added using the rudder effectiveness value determined in wind tunnel experiments and the measured stagnation pressure. These are then added to the jet control moments.

The most important problem for evaluating the flight properties during hovering flight and transitional flight is the problem of calculating the statistical distribution of the control moments. This program uses the programs mentioned up to now as subprograms. During a prescribed time interval and at a frequency of 50 Hz, we determined the control moments, the frequency, the standard deviations and average values over a prescribed moment interval. The moment interval is divided into 100 classes and the frequency per class is determined. For the pitch control moments, we also introduce additional velocity classes with a constant step of 5 m/sec and 100 moment classes are maintained for each of the velocity classes. In this way we in principle obtain the following distribution for the pitch moments:




This distribution can be plotted against flight velocity. The average values then represent the variation of the trip moment as a function of flight velocity. The end points of the distributions specify a moment range in which, for example, 98% of all of the pitch control moments which occur are present. /31
For example, this has the following appearance.




## 4.3. Evaluation of the Flight Test Results from Conventional Flights

### 4.3.1. Manual Evaluation

No special remarks are necessary to describe the manual evaluation. It is only necessary to read off the flight data from the lists, and to make the corresponding diagrams, such as are usually used during the testing of conventional aircraft. In addition to the usual evaluations, we also determined the flight mechanical derivatives. We will only devote a little more effort to the exact determination of the frequency, damping and phase correspondence of the individual parameters for tumbling motion. It is important to know these data /32 accurately for applying the time vector method, see also [6]. The evaluation is done by means of a small computer program which evaluates the frequency, damping and phase relationships from the measured flight parameters using the method of least squares. A weighting according to the average deviation of the measured points from the corresponding average value is also made.

### 4.3.2. Evaluation Programs

Programs for the evaluation of conventional flight were developed in order to determine the flight mechanical coefficients and derivatives from the flight test results. In order to determine the longitudinal motion coefficients, we used the Shinbrot method. In order to determine all of the coefficients at the same time, we used the regression analysis [7] for this special task. This was also programmed. The regression analysis has the distinct advantage that no special flight maneuvers are necessary. All of the necessary information can be obtained from any arbitrary measured flight with arbitrary disturbances. In this way the flight time expenditure could be held to a minimum. The principle of the method is the following:

Out of observations made during the flight tests, each observation contains all the necessary measured values. Using the equations of motion of the aircraft, it is possible to establish an equation for each degree of freedom for each observation. In order to determine the k unknowns, in this case the coefficients and the derivatives, k equations are required which result from k observations. Since the number of observations n is considerably larger than the required k equations, the remaining (n-k) equations are used to improve the result using statistical methods. In other words, stochastic influences /33 are eliminated. Even though the results with simulated flights were very good, the method in practice gave only a few useful results because of the fact that the measurement accuracy of the available measurement installation was not sufficient for this task. This meant that we were restricted to the results of the manual evaluation. The Shinbrot method also failed because of the same difficulties. /34

## 5. Flight Properties of the Do 31 for Covering Flight and Transition Flight

### 5.1. General Remarks

There are a number of requirements and recommendations for the flight properties in the VSTOL range. The best known and most used of these are the AGARD report No. 408 [1], which is summarized in a new version in report No. 577 [2]. Based on the requirements for conventional flight, the USAF has published VSTOL flight property directives under the MIL-F-83300 [3]).

In the following sections we will compare the flight properties of the Do 31 and the recommendations of the AGARD report No. 577 and the directives MIL-F-83300 as far as this is possible.

We will use the AGARD report as a basis of comparison, because it is easier to apply to the special VTOL aircraft having automatic stabilization.

## 5.2. Characteristic Data of the Control System and Stabilization System

The mechanical properties of the control system are very important especially for VSTOL aircraft during hovering flight and slow flight for the evaluation of the flight properties by the pilot. Therefore an entire chapter is attributed to this in the AGARD report [2]. Figure 7 shows the most important data of the Do 31 compared with the recommendations of AGARD and MIL. The numerical data for MIL correspond to a velocity /35 which is smaller than 50 kts and applies only for the "Level 1", i.e., they refer to the desired optimum range.

The table shows that the data of the Do 31 control system has the order of magnitude of the recommended values. One exception to this are the breakout forces and the control force gradients, which are considerably larger for the Do 31, especially for yaw control. However, the pilot never complained about this, but evaluated it as acceptable, see also [4]. Consequently we may conclude that for an attitude-stabilized aircraft, it is better to have somewhat higher breakout and control forces so that the pilot cannot disturb the controller too easily.

The table also shows that there are no AGARD or MIL recommendations for a number of important data of the control system, because up to the present there was insufficient data available.

## 5.3. Longitudinal Stability and Controllability

### 5.3.1. Control Accelerations and Trim Moments

We were especially interested in problems associated with the required trim moments during transition and the control accelerations used during maneuvering at the time we evaluated the flight test results. First of all the control reserves for the pitch axis are smaller than the reserves for the other axes because the control moments are produced through bleed air from the drive engines, which again influences the thrust of the drive engines. Therefore we cannot exceed a certain bleed air quantity.

In addition, we determined a large increase in the required trim moment as the flight velocity was increased during the first hovering flights. Depending on the flight conditions, it can reach the magnitude of the control capacity. /36

Figures 8 and 9 show the variations of the pitch control moments with time during a typical takeoff transition and during a typical landing transition. We can clearly see the close relationship between the trim moment and the flight velocity. Figures 10 and 11 give a statistical evaluation of these variations and the results have been evaluated as a function of flight velocity. The figures show that during the transition, considerably less control moment is required for maneuvering (scatter range) than is required for trimming. Also the changes in the trim moment are very clear which occur during the turn on or turn off of the lifting engines, when the flaps are moved or when the nozzle deflection angle is changed during the operations. The trim during transition is primarily produced by the engine thrust contribution, the aerodynamic pitch moment which increases with increasing velocity, and the pitch moment which is the consequence of jet interference. The aerodynamic pitch moment depends on the velocity and angle of attack. The jet-induced pitch moment depends on the engine thrust and deflection angle. For this reason the trim moments for takeoff transition have a linear to convex variation as a function of velocity. For landing transition, they are slightly concave because the takeoff transitions are flown with a higher thrust level. This is even more clear from Figure 12, which shows the variation of the trim moments as a function of velocity for a large number of transitions. In addition we can see the influence of a transition technique on the trim from the figure. At the beginning of the tests (low test numbers) we carried out flights at large negative angles of attack, especially during takeoff transition so as to obtain very short transition times. This led to large amounts of trim which amounted to almost the /37 order of magnitude of the available control moment. Later on (high test numbers) we flew with positive angles of attack which resulted in a reduction of the trim.

The pitch controllability during hovering flight was only a secondary problem compared with the problems mentioned above. Nevertheless, Figure 13 shows the statistically evaluated control accelerations for three hovering flights compared with the AGARD and MIL recommendations. Since there are no direct indications of control accelerations for MIL, but instead a certain position change after one second is specified, we calculated the required limit by considering a switching delay and displacement time delay of 0.2 seconds. The diagram shows that for example if 98% of all test data are considered, the MIL minimum limit was only barely achieved during one test flight and the control accelerations were usually lower.

The influence of the type of stabilization system on the magnitude of the required control accelerations for maneuvering is another interesting aspect. For AGARD [2] a distinction is already made between attitude stabilization, angular velocity stabilization and acceleration stabilization. The lowest control accelerations are specified for attitude stabilization. Figure 14 can be looked upon as a confirmation of this situation. During this experiment the pilot forgot to turn on the controller when taking off. He only did this after one-half of the transition was already over. One can clearly see a considerable reduction in the scatter range of the pitch control moments, after the controller had taken over the stabilization of the aircraft.

### 5.3.2. Dynamic Longitudinal Stability /38

The dynamic properties of the Do 31 are primarily determined by the controller and the engine dynamics during hovering flight and during transition flight. Even though the test pilots had the option of flying the aircraft in the pitch axis without stabilization for a short time, according to statements of the pilots, longitudinal stabilization is absolutely required for commercial use of VTOL aircraft. Figure 15 shows a comparison of pilot activity with and without the controller when the pitch attitude changes were controlled. It can be seen that in the control case, the pilot has much less manipulations with the stick.

A large number of tests were required to determine the setting of the controller, because no adaptation was available. The entire flight range to be controlled from hovering flight up to wing supported flight is covered by a single controller setting. Since the rudders are moved in parallel with the VTOL control installations, there is a considerable change in the circular amplification as the flight velocity increases, except for the aircraft dynamics caused by aerodynamics itself. The problem of the controller setting consisted of the following: sufficiently short time constants must exist for the hovering flight phase and at the same time, controller oscillations must be avoided in the range of high flight velocities. Figure 15 shows that for the controller setting selected for the Do 31, there are transient oscillation times of 2 - 3 seconds during hovering flight. In [2], shorter transient times are required: $T_{90}$ = 1 - 2 seconds; however, this higher inertia behavior was never objected to by the pilot. Probably this larger transient time is better suited for the size of the aircraft.

Figure 16 finally shows the reaction of the aircraft to a jump in the stick deflection, for an average transition velocity of V = 80 kts. The transient time is lower here but there is no overshoot here.

The aircraft has a similar dynamic transient behavior when /39 the pitch attitude preselection is activated, as already mentioned above. When the preselected pitch attitude is triggered with the button located on the control stick, the command signal moves to the preselected position at a rate of 5°/sec (see Figure 17). The aircraft then follows this direction signal with a delay of about 2 - 3 seconds.

The requirements for dynamic longitudinal stability according to AGARD and MIL are approximately the same. It is required that there is no divergent behavior and the superimposed oscillations must have certain frequency and attenuation values. These requirements are satisfied by the Do 31 using controllers, because the transient behavior is aperiodic and there is no superimposed oscillation.

The table given in Table 7 shows the other properties associated with longitudinal stability and the variations of the control forces.

## 5.4. Side Stability and Side Controllability

### 5.4.1. Roll and Yaw Control Accelerations

In order to obtain data for designing the control system of future VTOL aircraft, we gave special attention to the evaluation of the control accelerations used for the side motion as well. In contrast to the pitch control moments, we found no dependence on the flight velocity for the roll and yaw control accelerations. Instead the magnitude of the control impulse is controlled by the maneuver to be carried out and the velocity of the control signal inputs. /40

This is shown in Figure 18. This is a fast curve change during hovering flight at about 20 kts. The pilot attempted to fly a coordinated curve, because he gave stick inputs as well as pedal inputs. The largest roll control acceleration occurs during the first curve change, because the roll command as well as a relatively large and fast yaw velocity signal are superimposed upon one another. In the second curve change, the control accelerations are lower because the maneuver occurs more slowly. On the other hand, during the third curve change we find the largest yaw control acceleration. The diagrams also show the minimum control accelerations according to [2, 3]. Accordingly, one can see that both specifications will result in sensible criteria for the roll axis. On the other hand, the values required for the yaw axis are too high, especially as far as the specifications of [3] are concerned.

The conditions are more clear if we observe the following Table 2. We show the maximum values of the control accelerations which occurred during various flight maneuvers and compare these with the specifications [2] and [3] and with the maximum values which occur in the Do 31. The latter apply for an average velocity of 100 kts.

See the table below. /41

TABLE II *

| Maneuver | $\ddot{\varphi}_{max}$ | | | $\ddot{\psi}_{max}$ | | |
|---|---|---|---|---|---|---|
| | Eval. | Avail. | AGARD | Eval. | Avail. | AGARD |
| Vertical takeoff | 0,27 | 1,03 | 0,2 – 0,4 | 0,16 | 0,65 | 0,1 – 0,5 |
| ILS approach and vertical landing | 0,27 | 1,03 | 0,2 – 0,4 | 0,17 | 0,65 | 0,1 – 0,5 |
| Lifting engine turn-on | 0,39 | 1,03 | 0,2 – 0,4 | [illegible] | 0,65 | 0,1 – 0,5 |
| Fast takeoff | 0,25 | 1,03 | 0,2 – 0,4 | 0,05 | 0,65 | 0,1 – 0,5 |
| IFR approaches, correction of prescribed ILS deviations | 0,60 | 1,03 | 0,2 – 0,4 | 0,43 | 0,65 | 0,1 – 0,5 |
| Hovering flight: start of curves | 0,40 | 0,76 | 0,2 – 0,4 | 0,12 | 0,40 | 0,1 – 0,5 |
| Hovering flight: sideways displacement | 0,23 | 0,76 | 0,2 – 0,4 | [illegible] | 0,40 | 0,1 – 0,5 |

* Translator's note: Illegible in foreign text

When comparing the numerical values, one must remember that the maximum values found are only short time peaks, see Figure 18. Therefore, it is not immediately obvious that these large values are absolutely necessary. This is only true for the control system with electrical actuators used in the Do 31. If there were smaller installed controller accelerations, there would have been the danger of reaching and maintaining the maximum value for an extended time period, which could lead to controller instabilities or to burnout of the actuator motors. However, if hydraulic actuators and nonlinear controllers are used, these difficulties do not exist.

In addition to the maximum values, we evaluated the control accelerations according to their statistical distribution, see Figures 19 and 20. These figures show that, for example, 95% of all control accelerations used for maneuvering by the controller and the pilots are below the minimum limits specified in [2], and that large values are rare. The outer curve for the roll control accelerations is a particular case and has a bulge at 80%. The reason for this is the fact that both drive engines had different thrust levels over part of the evaluation time, and the pilot only became aware of this after a certain time. /42

We may summarize the control acceleration problem as follows: the initial large accelerations around the roll axis and yaw axis originally planned for trimming an engine failure of the Do 31 have in the control system now installed the order of magnitude which is required to provide good mobility of the aircraft. In addition, the evaluated flight test results have confirmed the AGARD recommendations for the design of the control system for hovering flight.

### 5.4.2. Control Sensitivity and Linearity

The data on control sensitivity are already contained in the table of Figure 7. Here we will compare the linearity specified by [2] and [3] with the data for the Do 31. According to AGARD [2] and MIL [3], linearity of the roll acceleration and yaw acceleration with control deflection is required, especially at small deflections. At large deflections, the control acceleration should at least not change suddenly or it should not change sign. Figure 21 shows the corresponding variations for the roll acceleration and the yaw acceleration. It can be seen that this requirement is satisfied. The bends in the variation of the roll control acceleration are produced by reaching the free running rotation rate in one lifting engine gondola, or by reaching the maximum permissible rotation rate in the other lifting engine gondola.

### 5.4.3. Coupling of Roll and Yaw Axes

The control deflections around the roll axis result in a yaw moment because of the fact that the lifting engines are installed obliquely. This moment must be controlled by the controller. Figure 22 a shows the coupling between the roll axis and the yaw axis for pure roll control inputs during hovering flight. The figure shows that the yaw actuator requires about 50% of the roll control motor deflection for compensating the undesired yaw moment.

If the velocity is non-negligible, this coupling can be expressed by the ratio of the sideslip angle and roll angle. According to [2], this value should satisfy

$$\left(\frac{\Delta\beta}{\Delta\phi}\right)_{max} < 0,5$$

According to [3], only a sensible correspondence between sideslips to the right and a roll controlled deflection is necessary, as well as a linear relationship between the sideslip angle and roll angle.

Figure 22 b shows the evaluated conditions for average transition velocities. The specifications of MIL are satisfied, but the ratio $\Delta\beta/\Delta\phi$ specified in [2] is too large for the Do 31. The practical effect of this fact is in the difficulty for the pilot of achieving large side velocities at moderate roll angles. During a ILS approach, side corrections were achieved by course changes and not by letting one wing hang. This can also be seen in Figure 23 where, in spite of the large roll angles, only small sideways accelerations are built up. The correction of the sideways ILS deviation required ten seconds from one point.

### 5.4.4. Dynamic Side Stability /44

As already mentioned in the chapter on dynamic longitudinal stability, the dynamic side stability properties are primarily determined by the controller and the engine dynamics. Only one controller installation for the roll and yaw axes is planned for the entire transition range. This leads to the center of problems already mentioned.

Figure 23 shows a reaction of the aircraft for an average transition velocity of 70 kts to a roll input. The return of the stick deflection to zero can be looked upon as a jump input. Therefore the transient time for the roll axis is also about 2-3 seconds. The time evaluated here up to 90% of the final nominal position $T_{90}$ is:

$$T_{90_{Roll}} = 2.3 \text{ sec.}$$

The time delay between the stick input and the beginning of the reaction of the aircraft is about 0.2 - 0.3 seconds depending on the flight state and the lifting engine thrust level.

Figure 24 shows the corresponding conditions for the same flight velocity and for jump pedal inputs. Since we have angular velocity stabilization for the yaw axis, the transient time is somewhat shorter. For hovering flight the time constant is 1.3 seconds, see Figure 7. For V = 70 kts we found a time constant of about 0.8 seconds. The time delay between pedal input and the beginning of the reaction of the aircraft is somewhat shorter for the yaw axis than for the roll axis. This is because the increase in the lifting engine thrust is associated with a time delay of 0.2 - 0.3 seconds. On the other hand, the rotatable nozzles can be operated with practically no delay. /45

Figure 24 also shows that the pedal inputs allow a faster correction of ILS side deviations than the pure roll inputs shown in Figure 23. In addition, the variation of the roll angle shows that the controller gives a good compensation for the coupling moments produced by the pedal inputs.

## 5.5. Hovering Flight and Vertical Flight Trajectory Control

### 5.5.1. Ground Effect

According to MIL [3], there are no special requirements for flight with ground effect. However, the AGARD requires that when there is a ground effect, there should be no unsatisfactory properties such as shaking of the controls or surprising reactions of the aircraft caused by unsteady aerodynamic effects. Even though this is not the case for the Do 31, we must realize that

flight with the ground effect is not possible because of the recirculation and jet interference. Both problems will be discussed in special reports in detail and we will therefore only discuss their effects here. The flight mechanical effects of hot gas recirculation and jet-induced downwind consist of an increase in the sinking velocity and therefore an increase in the touchdown velocity on the ground. This can lead to increased undercarriage loads. Figure 25 shows the effects according to evaluations of the flight tests. The inlet temperature increase usually amounts to between 20° and 40° for normal vertical landings. The drive engine deflection angle depends on the remaining forward velocity and is usually not greater than 95-110°. Both effects result in an increase in the sinking velocity, so that the pilot had to descend into the ground effect with a maximum sinking velocity 1 m/sec. Before touchdown we had to slightly /46
increase the thrust so as to not produce excessive undercarriage stresses.

### 5.5.2. Vertical Acceleration

The two flight property directives [2] and [3] require a minimum initial acceleration without changing the pitch position of ± 0.1 g. There are several possibilities of producing a vertical acceleration with the Do 31. Figure 26 shows these possibilities within the framework of the normal variation range for hovering flight. It can be seen that the minimum initial acceleration required by the directives can be produced by increasing the thrust of the drive engines or of the lifting engines. However, the lower diagram in the figure shows the magnitude of the horizontal acceleration which is then produced at the same time. The figure shows that the coupling is much smaller for the lifting engines. In practice, the flight trajectory control was therefore primarily carried out using the lifting engine thrust, because also the time constant and therefore the response time of the lifting engines is about 3 to 4 times lower than those of the drive engines. This fact can also be seen from Figure 27 which shows the reaction of the aircraft to a jump increase in the lifting engine thrust.

The figure also shows one important aspect of using the engine thrust for control purposes. It can be seen that, when the lifting engine thrust lever is operated, the vertical acceleration of the aircraft begins before the rotation rate increases. The reason for this is that the fuel supply already introduces an increase in thrust because of the increase in exhaust temperature before the rotation rate increases. This produces a considerable thrust increase.

Figure 28 is similar to Figure 26 and shows the vertical /47
acceleration capacity for the average transition velocity of 70 kts for a drive engine deflection angle of 120°. Accordingly, the largest vertical acceleration can be produced by changing the longitudinal inclination. This fact was also considered in practice. In general, vertical flight trajectory changes during transition were carried out using longitudinal inclination at the higher flight velocities, but at low velocities they were carried out using the lifting engine thrust.

Figure 28 also shows the large coupling of the two axes. This means that the pilot must not only perform one function for vertical flight trajectory control, but must also compensate for the undesirable coupling effects by additional control manipulations. A direct lift control system would be very advantageous here.

### 5.5.3. Vertical Thrust

According to AGARD [2], a vertical thrust is required which results in a steady ascent velocity of at least 600 fpm while also taking into account the vertical velocity attenuation. No test flights for this were carried out using the Do 31, but from the ascent velocity variation for steep vertical takeoff, Figure 29, it can be seen that the vertical ascent capacity of the Do 31 is very large compared with the minimum values recommended in [2].

### 5.5.4. Horizontal Acceleration and Delay Capacity

/48

In order to be able to carry out transitions safely and with reserves, AGARD [2] requires a horizontal acceleration and delay up to 0.5 g. Figure 30 shows the acceleration values which were produced by the Do 31 during practical flight operations, compared with the theoretical possibilities. The figure shows that during takeoff transition, the required large horizontal accelerations are not available but, on the other hand, during landing transition the flown values are considerably smaller than the required values and the theoretically possible values. The reason for this is the fact that the takeoff transition is a maneuver which can easily be carried out by the pilot. On the other hand, the landing transition with the additional constraint of maintaining the glide path as well as the vertical landing at a selected landing point requires considerable skill by the pilot. This means that he cannot carry out the additional configuration changes in order to exploit the optimum delay. In particular, the desired delay value of 0.5 g seems to be too large for landing transition.

## 5.6. Behavior of the Aircraft in Case of a System Failure

By system failure we refer to the failure of an engine or the failure of a flight controller. In [2] and [3] for these cases it is required that there will be no unusual attitude changes, angular accelerations or sink velocities, so that the pilot is capable of avoiding dangerous situations or carrying out an emergency landing or at least he must be able to leave the aircraft under safe conditions. /49

First of all we should like to mention that both cases, controller failure or engine failure, did not occur during the practical flight operations. Nevertheless, controller failures and even engine failures were simulated in the test stand tests. The experiments showed that, if one channel of the controller fails, the pilot is still capable of flying the aircraft. However, it must be stated that he can only do this for a short time and the roll axis can only be controlled using the additional roll damping device. If the entire controller fails or if the engine fails, manual control is not possible. Therefore, in order to achieve a high operational safety of the controller, it was statically measured before each takeoff which, of course, consumes time and was not very accurate because of the alternating voltage amplifier technology. Therefore, the future design of the controller includes a three channel version (triplex system) and an essentially automatic test capability.

The failure of an engine can be controlled by the controller without any great loss. However, the altitude loss which occurs depends greatly on the reaction time of the pilot. In this case the lifting engines must be operated in the emergency thrust mode. Figure 31 shows the simulation of a drive engine failure during landing transition for a velocity of 100 kts. The roll attitude wanders by 5° and after 10-12 seconds, it takes on a stationary value of 2°. The altitude loss is about 10 m for a reaction and adjustment time of 3.5 seconds from the beginning of drive engine failure until the lifting engine emergency thrust level is reached. If a lifting engine fails, the deviations are smaller by the approximate factor of 2-3 because of the reduced thrust.

## 6. Special Flight Property Problems of the Do 31 for Conventional Flight Conditions /50

In this chapter we will discuss those flight property problems which can result because of the VTOL capacity of the Do 31. Detailed data on the flight properties for conventional flight are contained in [5] and [6]. The various configuration characteristics of the Do 31 compared with conventional transport aircraft and which are important for the flight properties are the following:

- Large roll moment of inertia because of the drive engine gondolas and lifting engine gondolas combined with a relatively small wing span.

- Large tail rudder in order to be able to satisfy the requirement for controllability of a drive engine failure for conventional takeoff.

- Relatively small rudder-wing separation.

### 6.1. Roll Controllability

The roll control was designed according to the roll controllability requirement of the old MIL-F-8785. Accordingly, a certain roll velocity must be reached in a specified time. Even though this requirement was only barely satisfied according to theoretical calculations, the pilot complained at the beginning of the flight tests about the excessive rudder effectiveness which in conjunction with the large roll time constant led to PIO (pilot induced oscillations) around the longitudinal axis. The reason for this divergence between the pilot evaluation and the flight property requirement is that in the case of MIL-F-8735 the desired roll controllability effect does not depend on the moment of inertia around the roll axis but on the span. Since in the Do 31 the roll moment of inertia-to-weight ratio and the aircraft geometry are greater because of the lifting engine gondolas than in conventional aircraft, this requirement leads to erroneous values in this case. The predicted difficulties in roll control are overcome by the planned installation of a roll damping device, which improved the aerodynamic roll damping by 150% and thereby reduced the excessive transverse rudder effectiveness as well as the roll time constant which had been too large. In spite of this, the pilots evaluated the maneuverability of the Do 31 around the longitudinal axis as being excessively high, corresponding to that of a fighter aircraft. /51

### 6.2. Damping of the Tumbling Motion

The short rudder moment arm combined with the large rudder leads to an excessively large induced side wind effect which has a large influence on certain dynamic derivatives. This then worsened the damping of the tumbling oscillation. The roll dampers, which were installed in order to control the roll, also improve the tumbling oscillation properties to the extent that the originally planned installation of a yaw damper became unnecessary. /52

## 7. Critical Remarks Regarding the Flight Property Requirements and Recommendations

### 7.1. General Remarks

The present report was structured according to the AGARD report No. 577 [2]. We wanted to show that this report at the time contains the best and most useful selection of possible VTOL flight property directives. It was produced from the older AGARD reports No. 408 and 408 A and already considers a number of results from concluded VTOL flight tests. The report was prepared by NASA with colloboration of an international group of experts within the framework of the AGARD Flight Mechanics Panel.

In spite of this, there are a number of deficiencies, which were published shortly after a report by the DGLR specialists group on flight properties appeared. This was presented to the AGARD during a flight mechanics panel meeting in the fall of 1971, see [8]. In contrast to this, the flight property specification for V/STOL aircraft [3] published by the USAF is not as easy to use for the design of V/STOL aircraft. This specification was produced in concordance with the specifications for conventional flight MIL-F-8785 B. In its present form it is more suited for STOL aircraft. For example, the automatic stabilization required for all VTOL aircraft is not contained in it. One positive aspect of this MIL specification is the philosophy of satisfying certain requirements using various "levels". For example, only specifications with the "Level 1" are to be satisfied in order to satisfy a mission and represent the highest possible requirements. For less important characteristics, it is possible to apply a less stringent criterion corresponding to "Level 2" or "Level 3". /53

Both specifications were written at the same time and published at the same time. In spite of this, there was no contact between the two groups of authors, so that no experience could be exchanged. This is a serious deficiency in both reports, because a coordinated report would have satisfied the requirements of the design engineers better, especially since experience with VTOL aircraft has been rather scanty.

## 7.2. Special Remarks and Improvement Suggestions

The main task for such specifications and directives should be to give a project engineer clear information during the design of a VTOL aircraft. One of the most important items is to know how much thrust should be installed so as to guarantee reasonable flight performances and properties and in order to cover engine failures in the case of multi-motor aircraft types. This most important point is not treated in detail by either of the specifications. It should be defined as follows:

- How large do the control accelerations have to be when all of the control organs are operated at the same time and if a thrust-to-weight ratio of one is to be maintained?

- How large do the residual control accelerations have to be in the case of an engine failure if all of the control organs are being operated at the same time and in order to maintain a residual thrust-to-weight ratio of one?

- How large do the residual control accelerations have to be around a control axis in the case of engine failure if one permits a residual thrust-to-weight ratio of less than one?

Based on the experience of Do 31 we can make the following recommendations, for example: /54

1. Thrust-to-weight ratio equals one should be satisfied if all three control axes are operated at the level of

the statistically evaluated control acceleration based on 95-98% of all data.

2. The maximum control accelerations around an axis should be at least those corresponding to the values of AGARD [2], but it is not necessary to maintain a thrust-to-weight ratio of one for this.

3. In the case of an engine failure, a thrust-to-weight ratio of at least one should be able to be maintained for simultaneous control accelerations around all axes amounting to 50% of the magnitude determined under one.

4. Also, in the case of engine failure, the maximum control acceleration around one axis should be at least 50% of the value specified under two.

The case of failures of the stabilization system is not specified in enough detail in the reports. One possible recommendation in this area is the following [8]:

- If there are no control and stability systems, no large changes in the control los should occur. In other words, the return from attitude stabilization to angular rate stabilization should only be permissible for one axis and it should not be possible to go from attitude stabilization to acceleration control. /55

The available recommendations for the yaw axis do not consider the fact that this axis is usually angular rate stabilized. In the case of [2] there are certain discrepancies for an attitude stabilization concerning the criteria for the dynamic behavior and the damping criteria. In addition, too much importance is attributed to the ground effects, in cases where it is dangerous for all VTOL aircraft to fly in the ground effect range for a long time. The problem really is a safe transition through the ground effect range.

## 8. Summary and Conclusion /56

The flight tests carried out with the Do 31 demonstrated the basic capacity of VSTOL operation with transport aircraft. Also some additional valuable data were obtained which are important for the further development in the direction of economical and safe operation. In spite of the number of problems, the Do 31 concept of a VTOL transport aircraft points in the direction of future development, see also [4]. A project design based on experience obtained with the DO 31 was prepared by Dornier in 1970 and given the name Do 31. This was in response to a request for a proposal by the BMVg (German Military Department) and the Lufthansa for a VSTOL transport aircraft. A number of problems which still exist in the Do 31 were solved. The Do 31 could also be used as an experimental vehicle for clarifying many operational problems. Many problems can only be dealt with for a short time during the testing phase, and many problems only occur as a result of tests.

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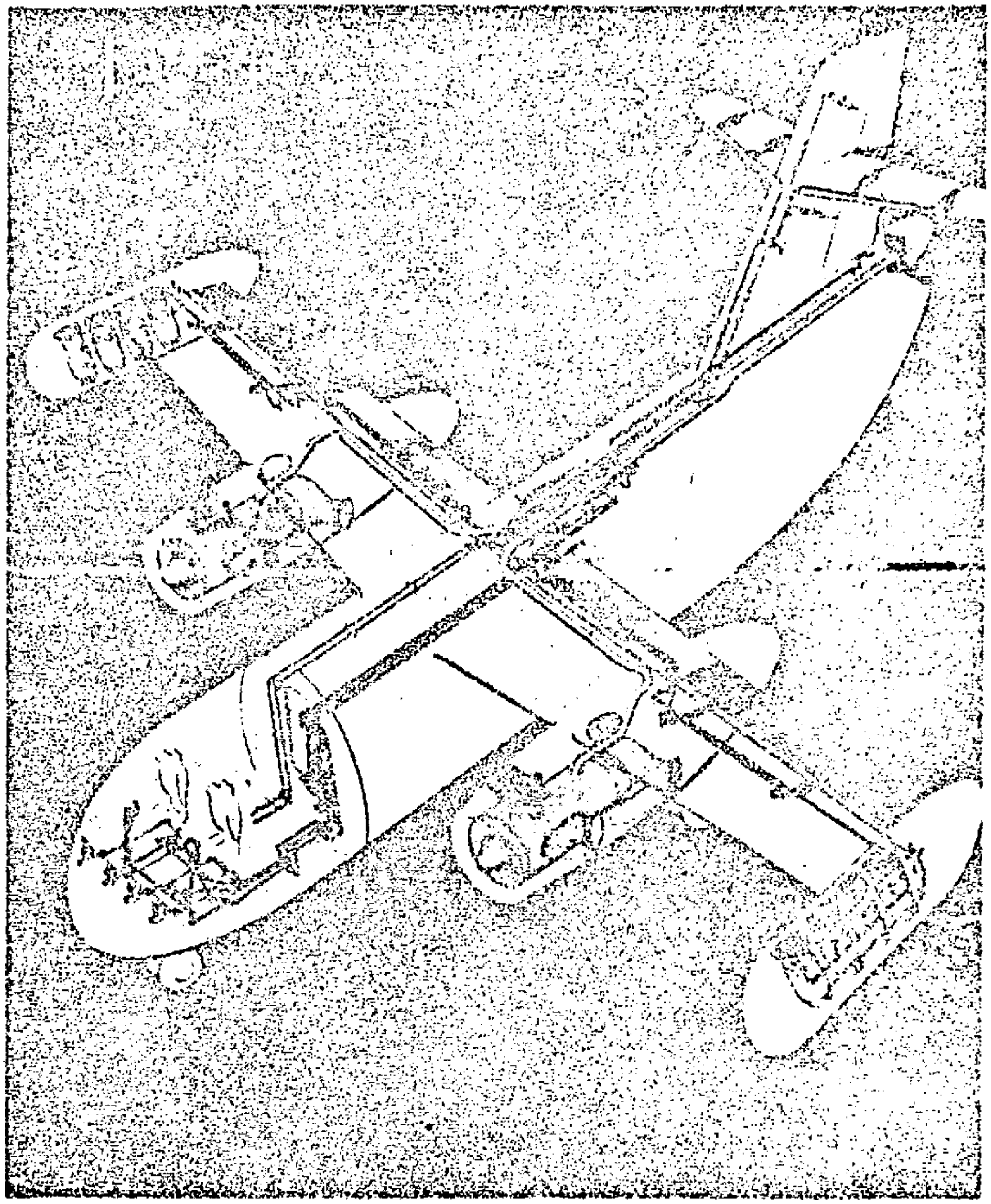

Figure 1. Schematic representation of the control system of the Do 31

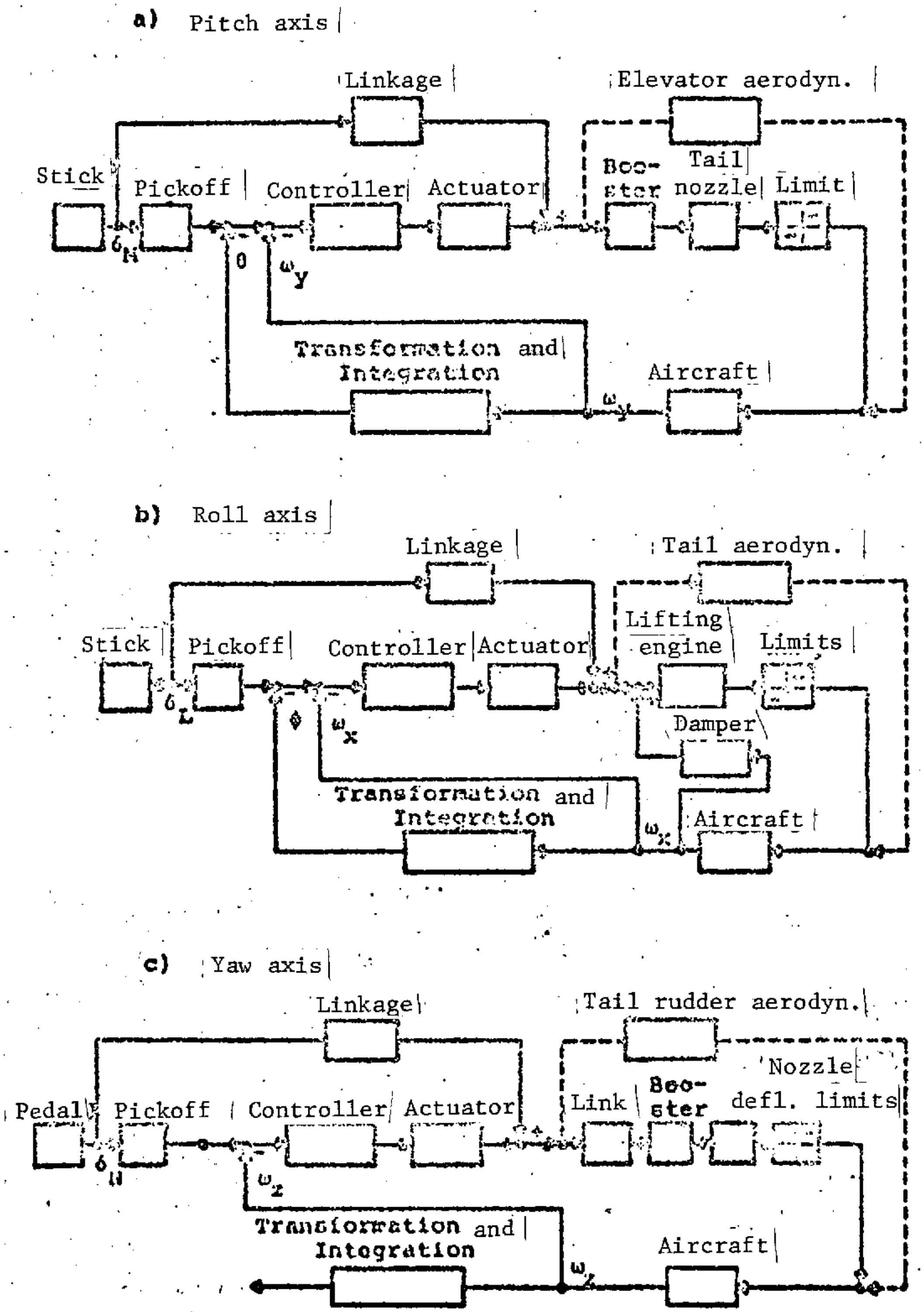


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Figure 2. Block diagram of the control and stabilization system of the Do 31 for the VTOL configuration.

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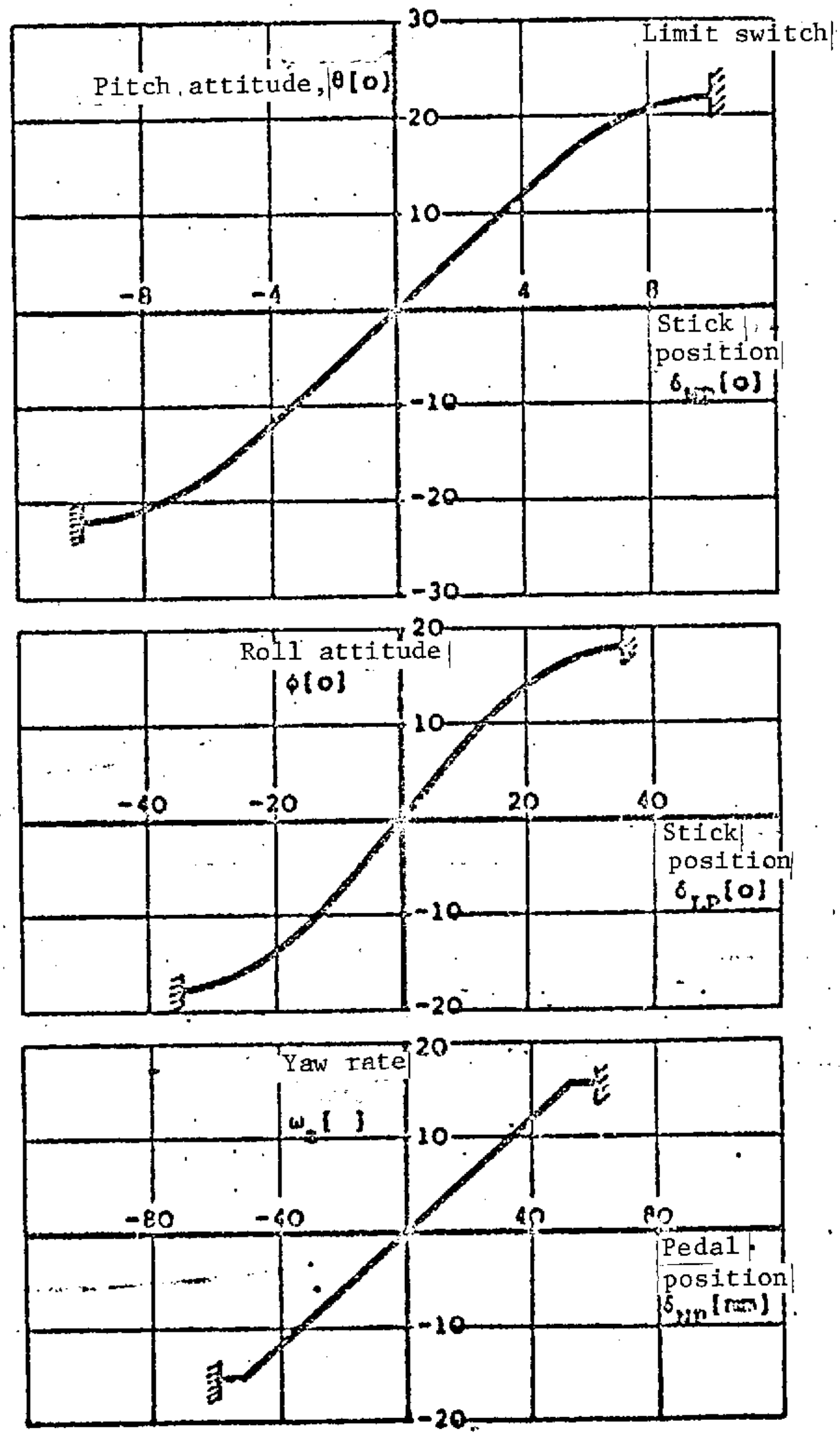


Figure 3. Correspondence of stick and pedal position with commanded aircraft attitude and angular rate

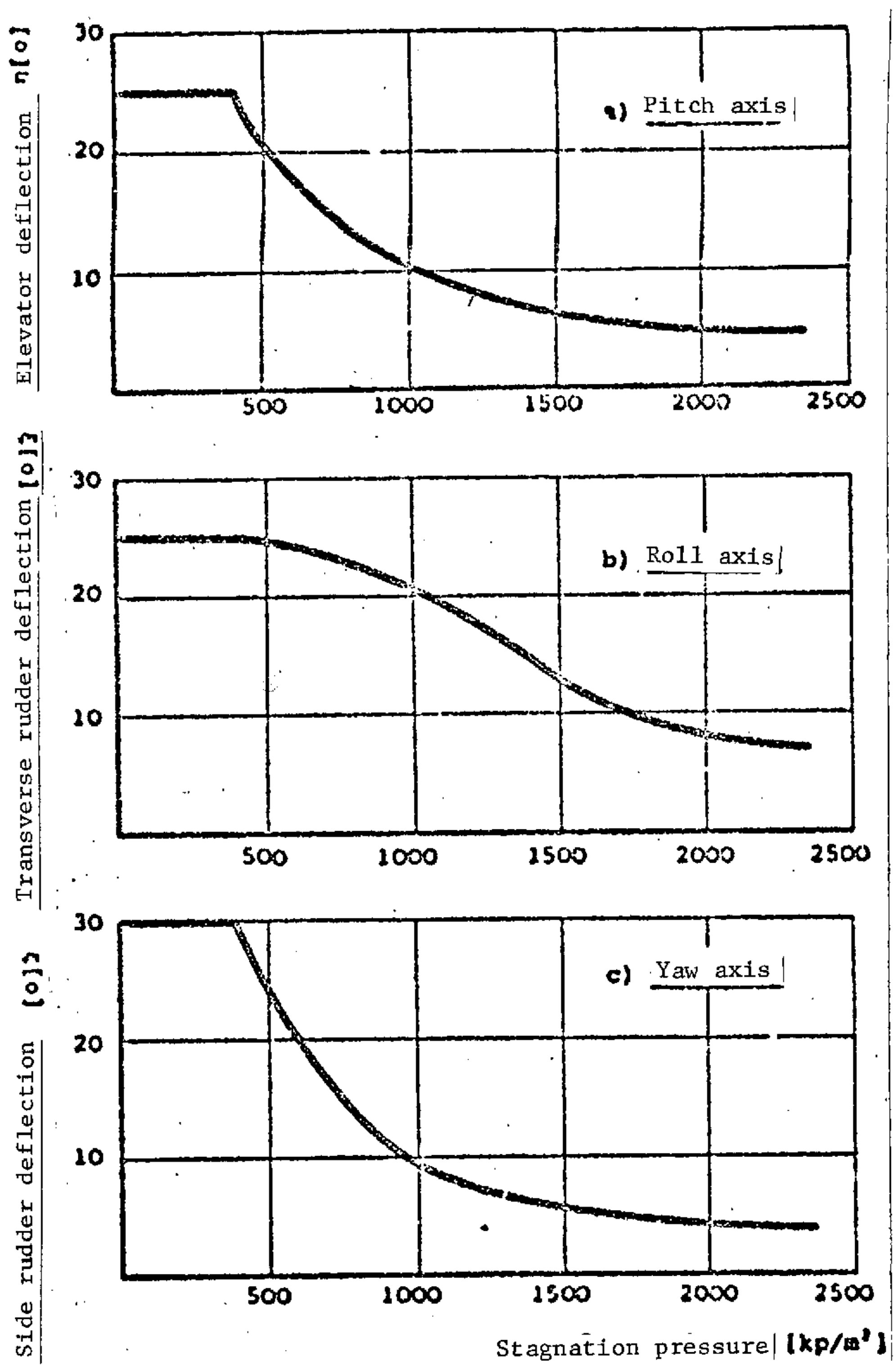


Figure 4. Stagnation pressure dependent limitation of the maximum rudder deflections

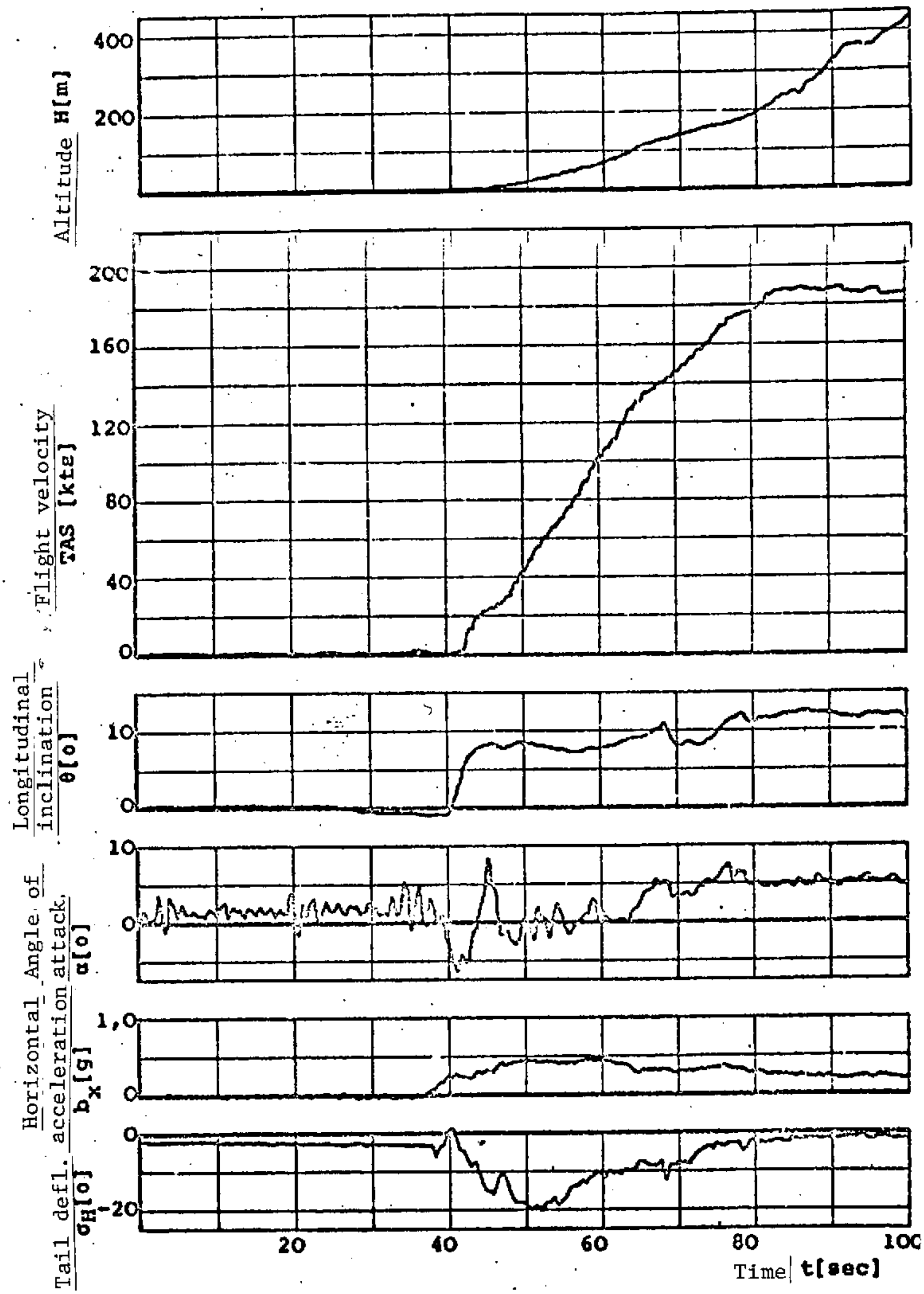


Figure 5a. Flight state variables during a vertical takeoff with transition

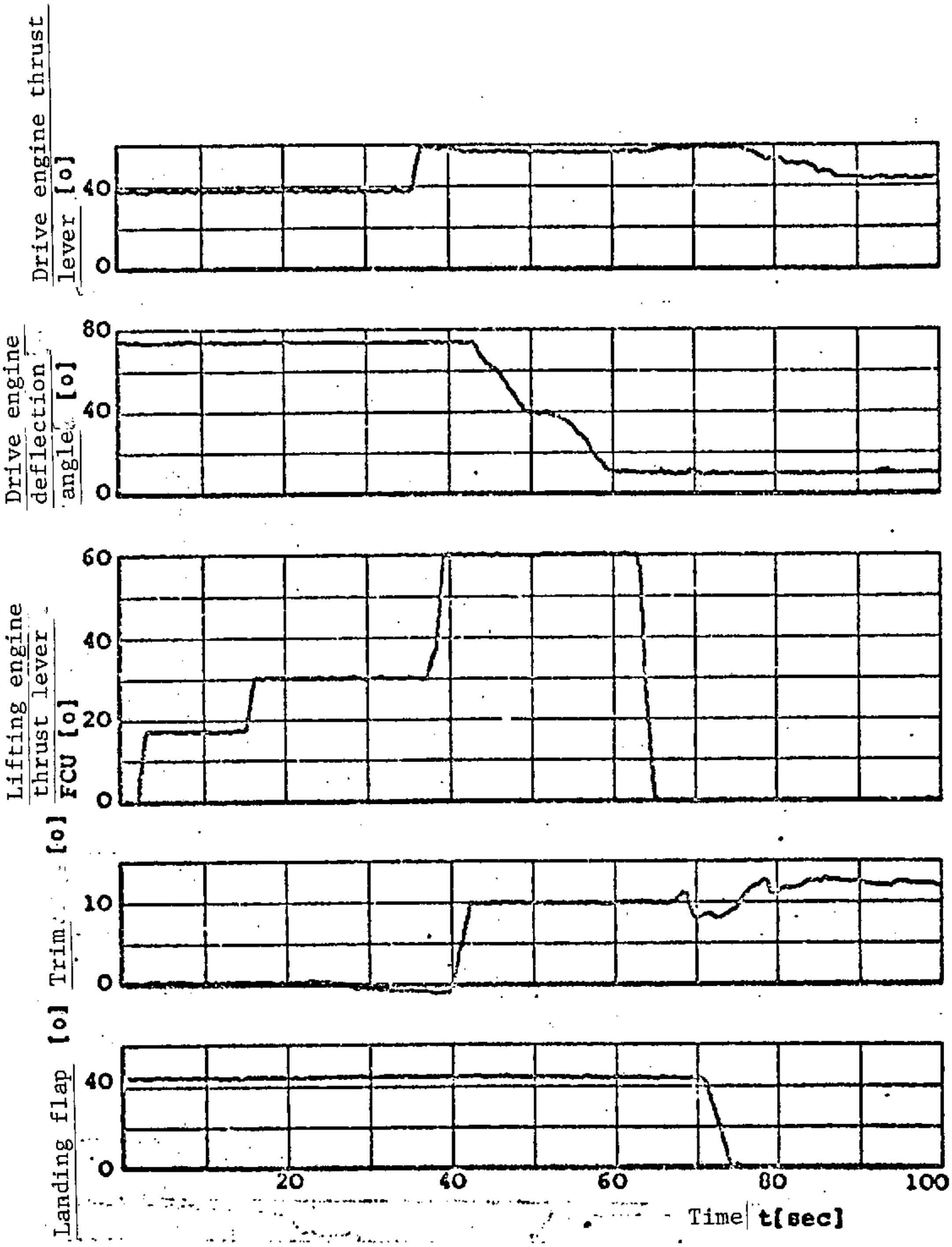


Figure 5b. Pilot activities during a vertical takeoff with transition

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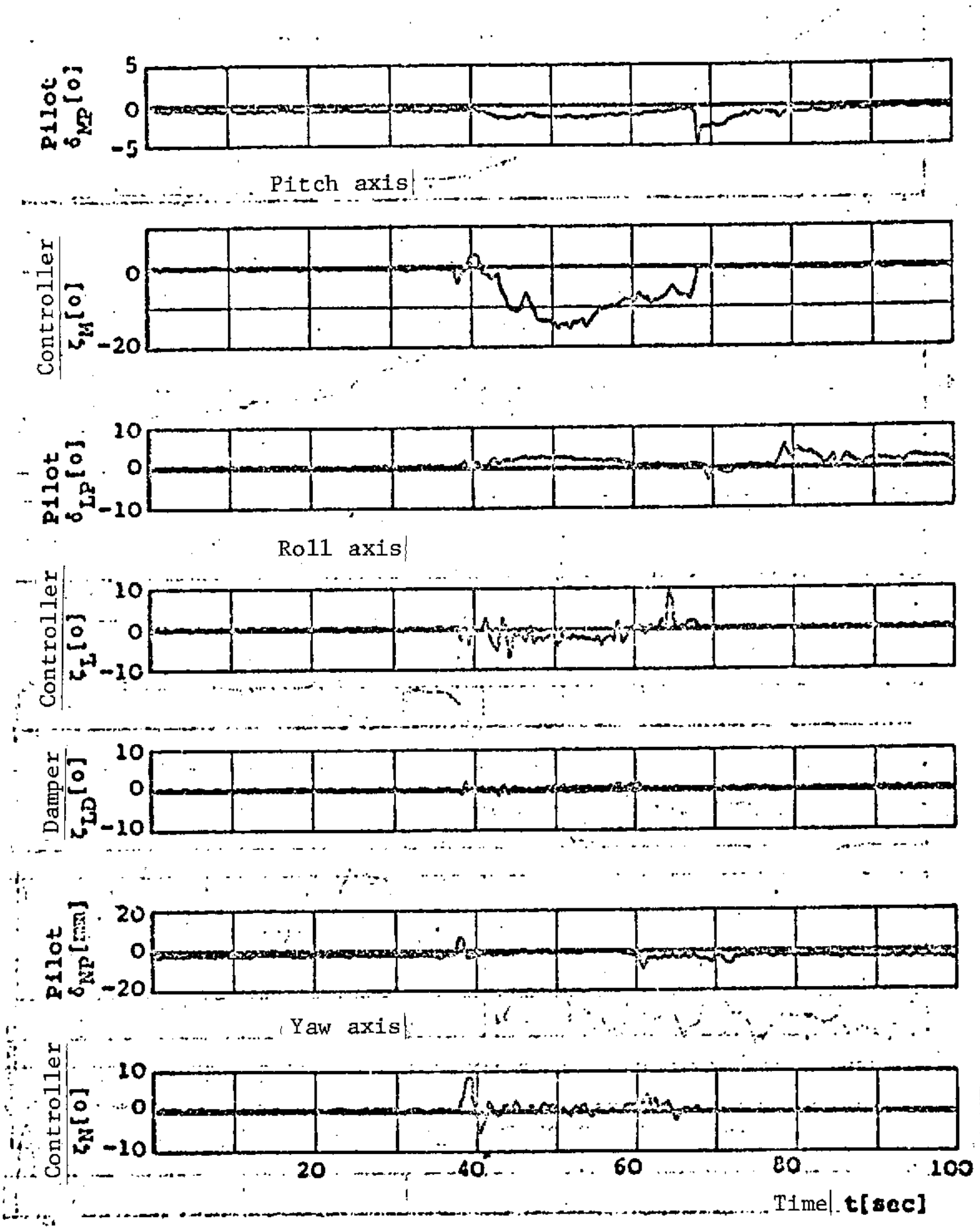


Figure 5c. Comparison of pilot and controller activities during a vertical takeoff with transition

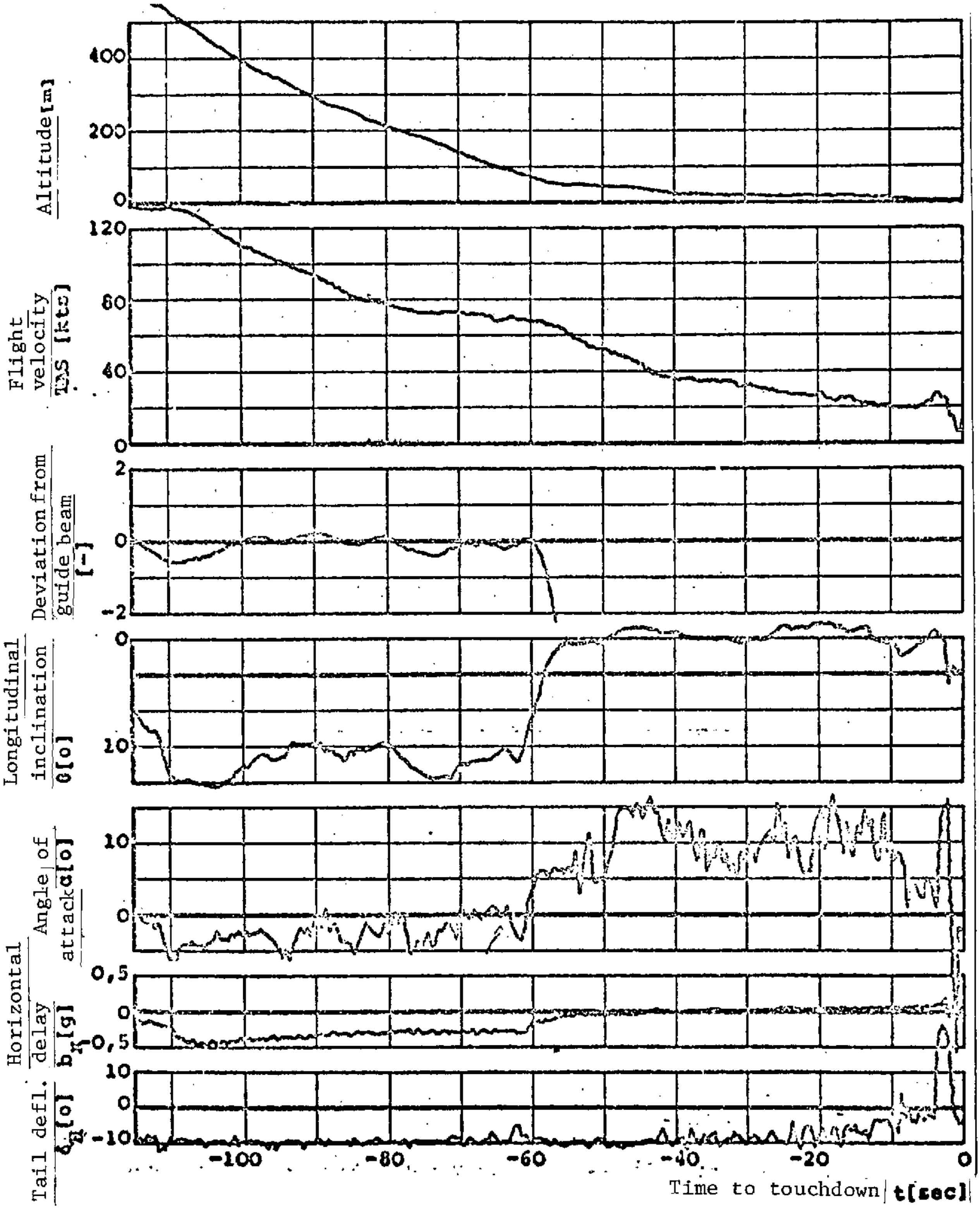


Figure 6a. State variables during a landing transition with vertical takeoff

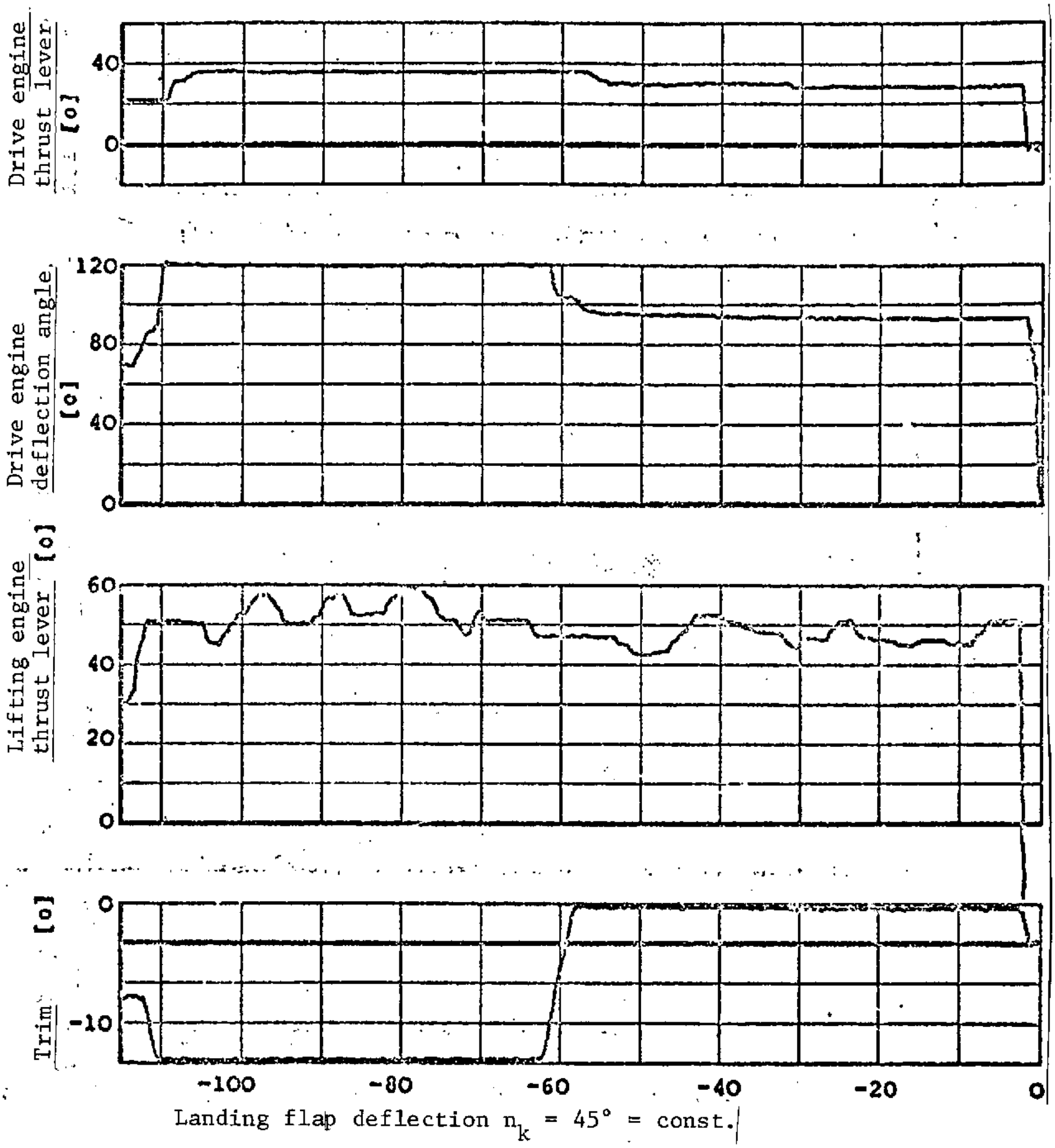


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Figure 6b. Pilot activities during a landing transition with vertical landing

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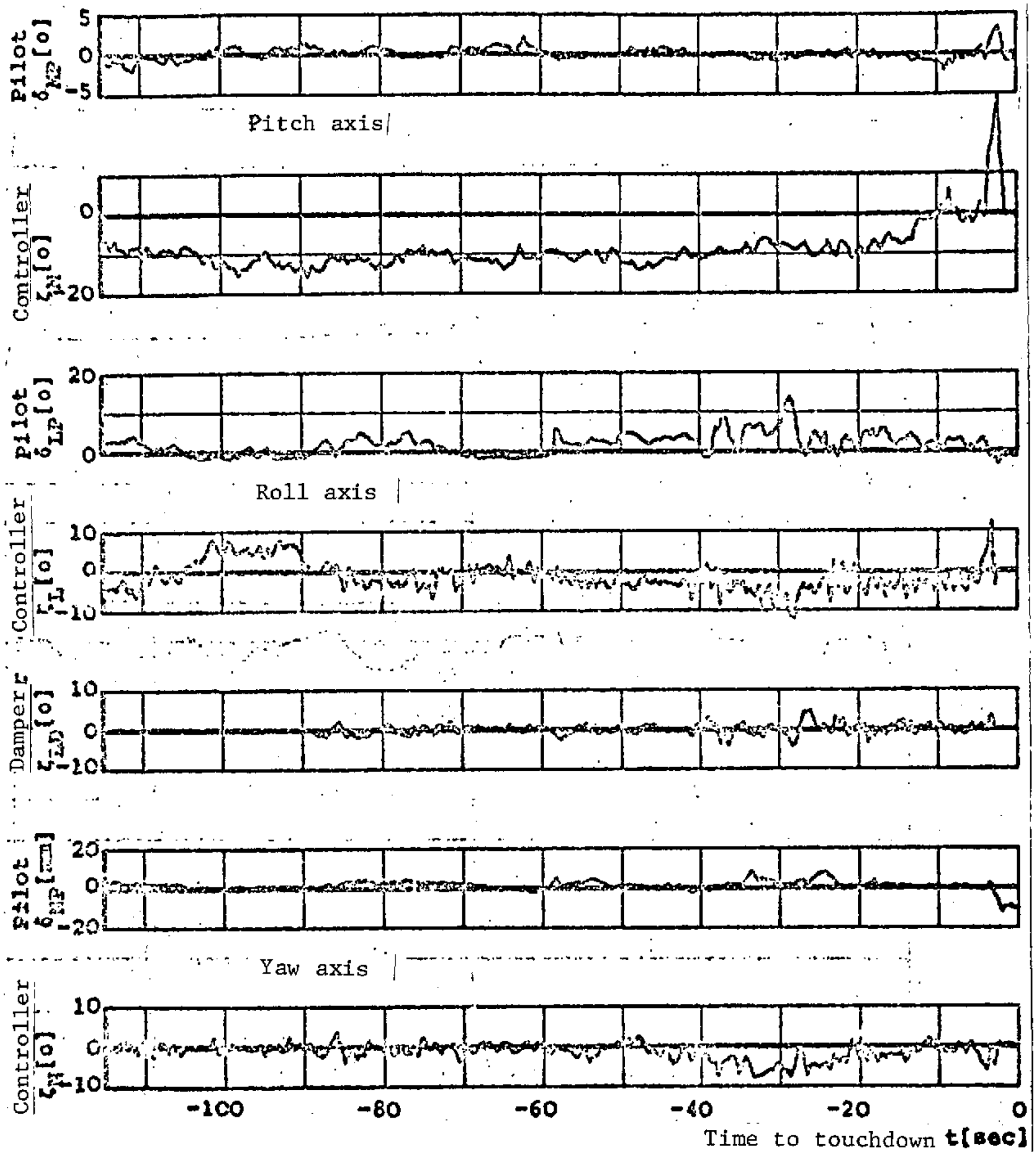


Figure 6c. Comparison of pilot and controller activities during a landing transition with vertical landing

| | Dimension | Roll axis | | | Pitch axis | | | Yaw axis | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Do-31 | AGARD | MIL* | Do-31 | AGARD | MIL* | Do-31 | AGARD | MIL* |
| VSTOL breakout force | lbs | 2,1 | 0,5 – 3,0 | 0,5 – 1,5 | 3,3 | 0,5 – 3,0 | 0,5 – 1,5 | 10,5 | 1,0–10,0 | 2,0–7,0 |
| Control force gradients | lb / in | 2,7 | 0,5 – 1,5 | 0,5 – 2,5 | 3,3 | 1,0 – 3,0 | 0,5 – 3,0 | 12,9 | 2,5–10,0 | 5,0–10,0 |
| Max. control force | lbs | 12,2 | 15 | 7,0 | Press. 30 tension 20 | 15 25 | ± 10,0 | 43 | 15 – 50 | 30 |
| Max. control | in | ± 4,65 | 3,0 – 6,5 | No data | ± 5,2 | 4,0 – 3,5 | No data | ± 2,05 | 2,5–4,5 | No data |
| Attitude change per control deflection | °/in | 7,0 Non linear | 3,0 – 5,0 | 4,0–20,0 | 6,0 Non linear | 3,0 – 5,0 | 3,0–20,0 | n.a. | n.a. | n.a. |
| Max. attitude change for max. control deflection | ° | ∓ 18 | No data | No data | ∓ 22 | No data | No data | n.a. | n.a. | n.a. |
| Time until reaching 90% of commanded attitude change $T_{90}$ | sec | 2 – 3 | 1 – 2 | No data | 2 – 3 | 1 – 2 | No data | n.a. | n.a. | n.a. |
| Eigenfrequency of the control system | 1/sec | 2,5 | No data | No data | 2,5 | No data | No data | n.a. | n.a. | n.a. |
| Damping ratio | – | 1,0 | No data | No data | 1,0 | No data | No data | n.a. | n.a. | n.a. |
| Angular velocity change per control deflection | °/sec / in | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 8,5 Non linear | No data | No data |
| Max. angular velocity change for max. control deflection | °/sec | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 14,5 | No data | 10,0 |
| Time for 15° course change | sec | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 1,1 | 1,0 – 2,5 | No data |
| Time constant | sec | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | 1,3 | No data | No data |

Figure 7. Characteristic Data of the Control and Stabilization (Illegible)

* MIL-F83380 values for level 1 and V<35 kts .

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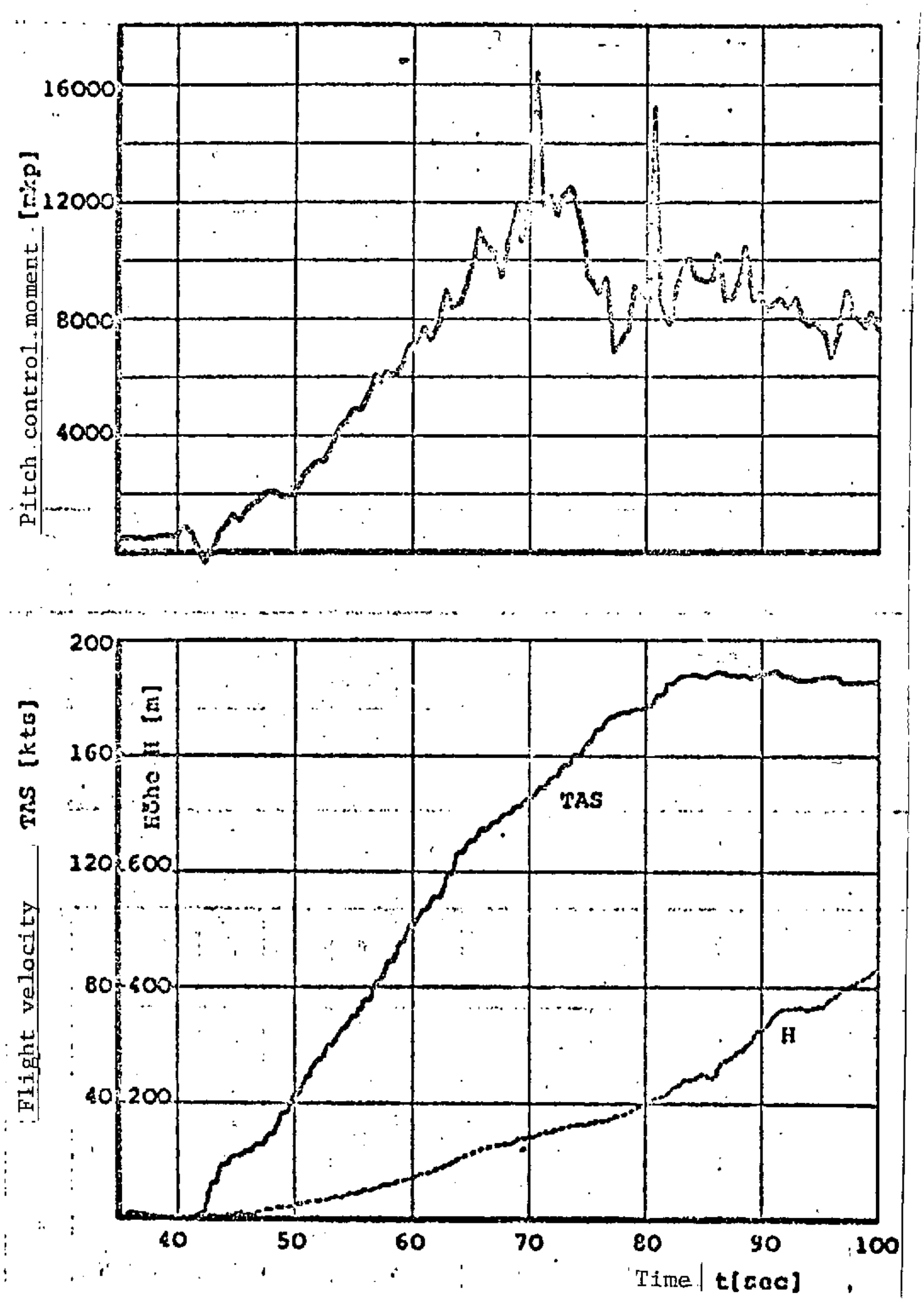


Figure 8. Variation of the pitch control moments during a typical takeoff transition.

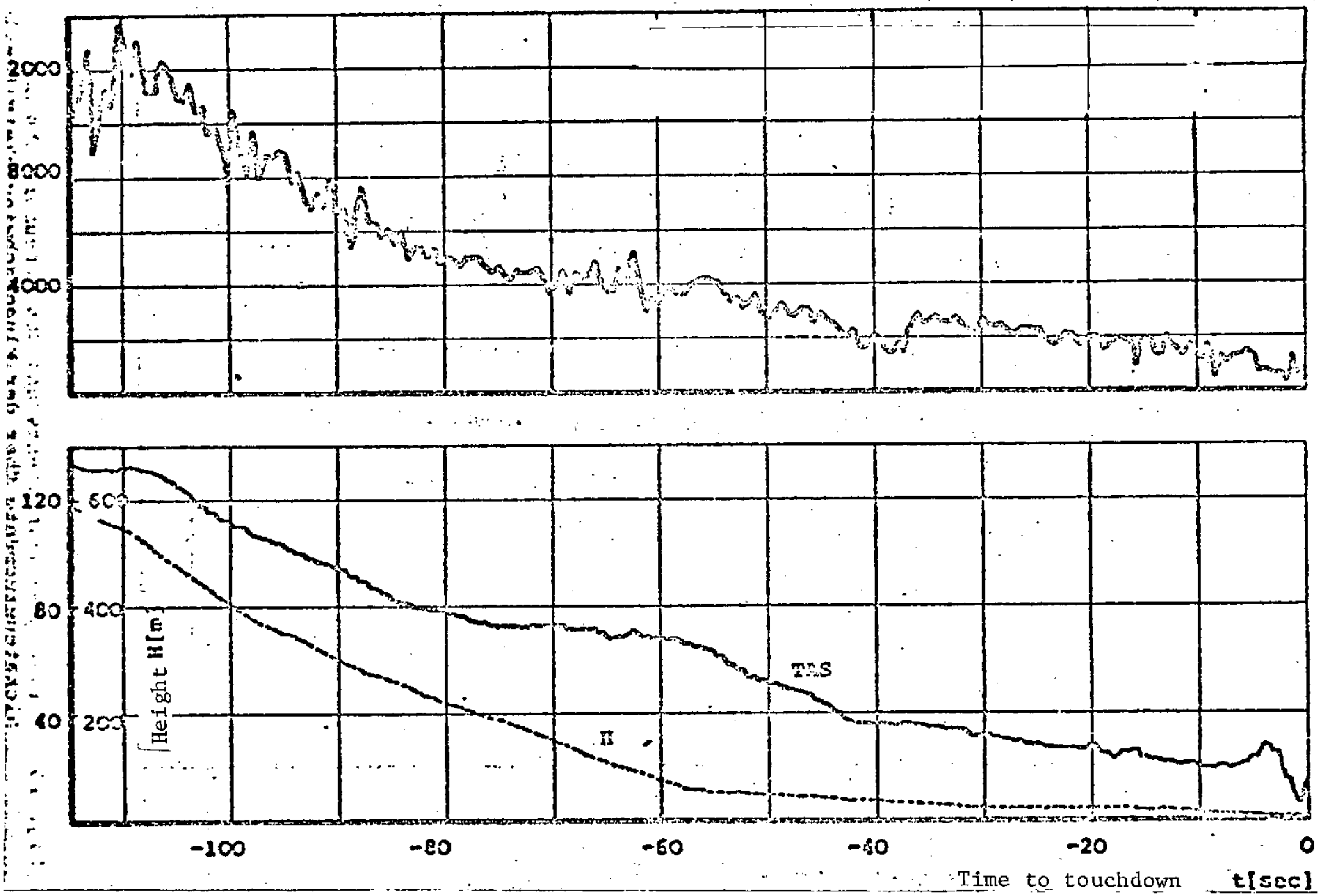


Figure 9. Variation of the pitch control moments during a typical landing transition

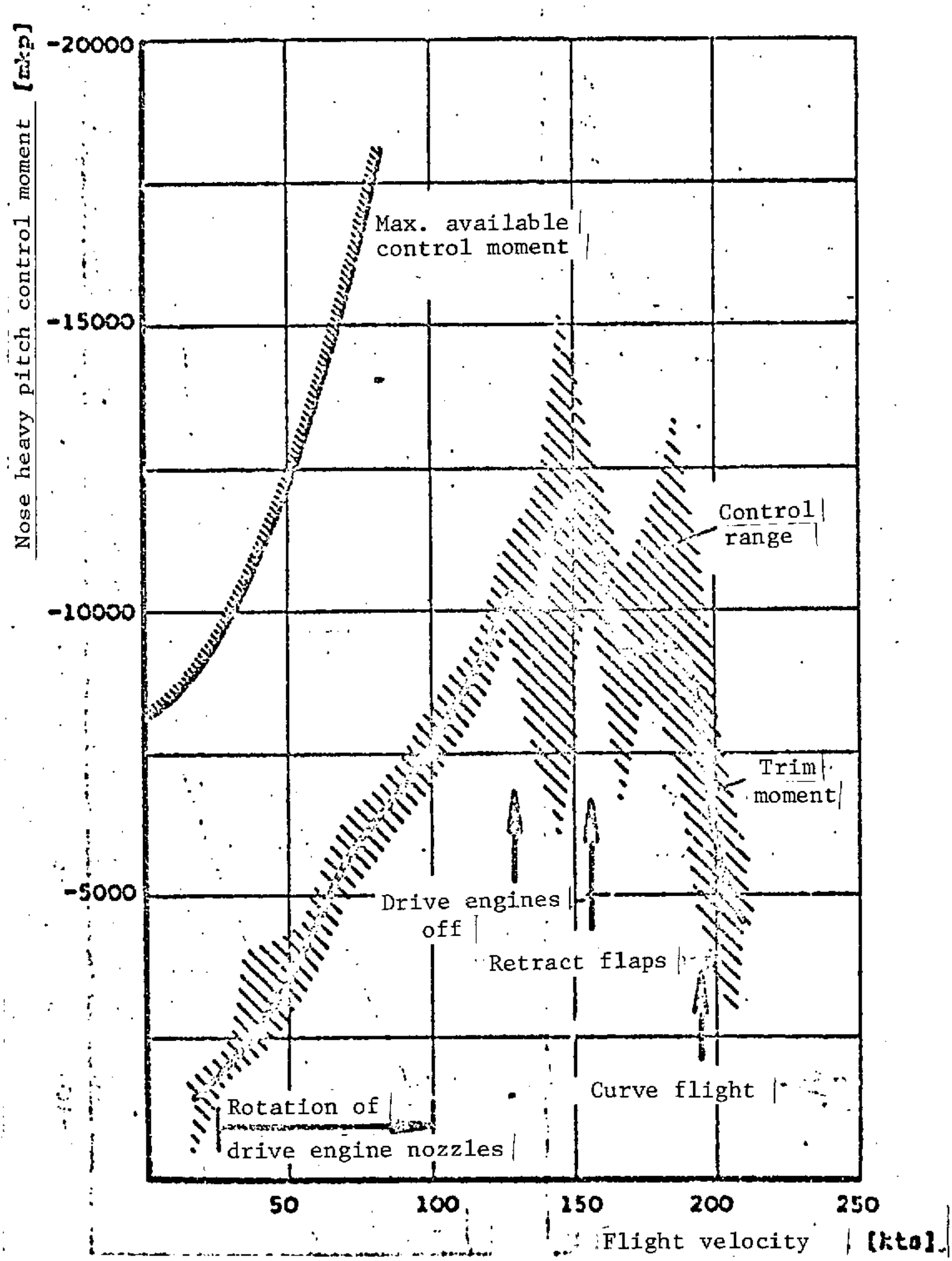


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Figure 10. Variation of the trim moment and the control range of the pitch control moments as a function of flight velocity for (illegible)

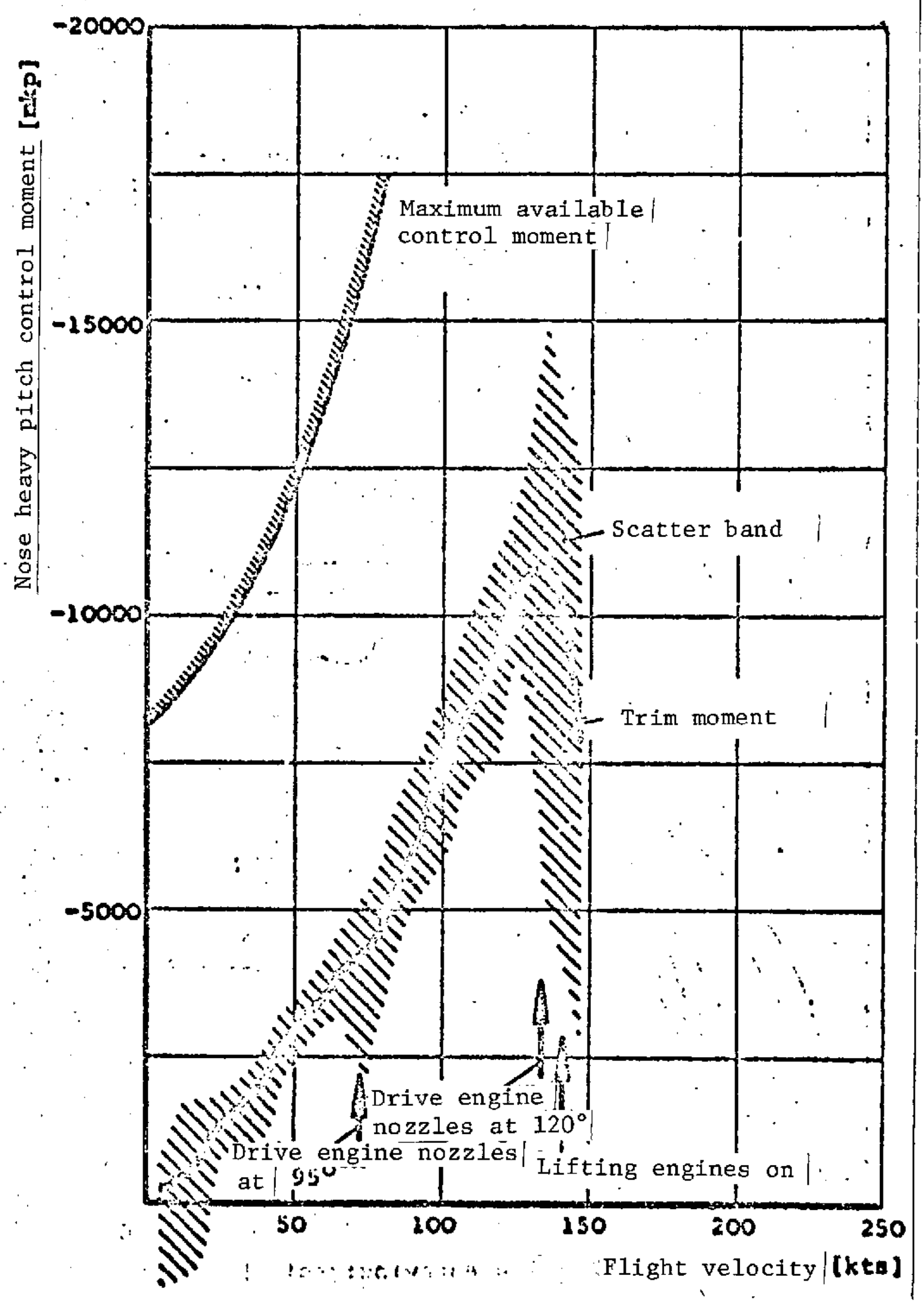


Figure 11. Variation of the trim moment and control region of the (illegible)

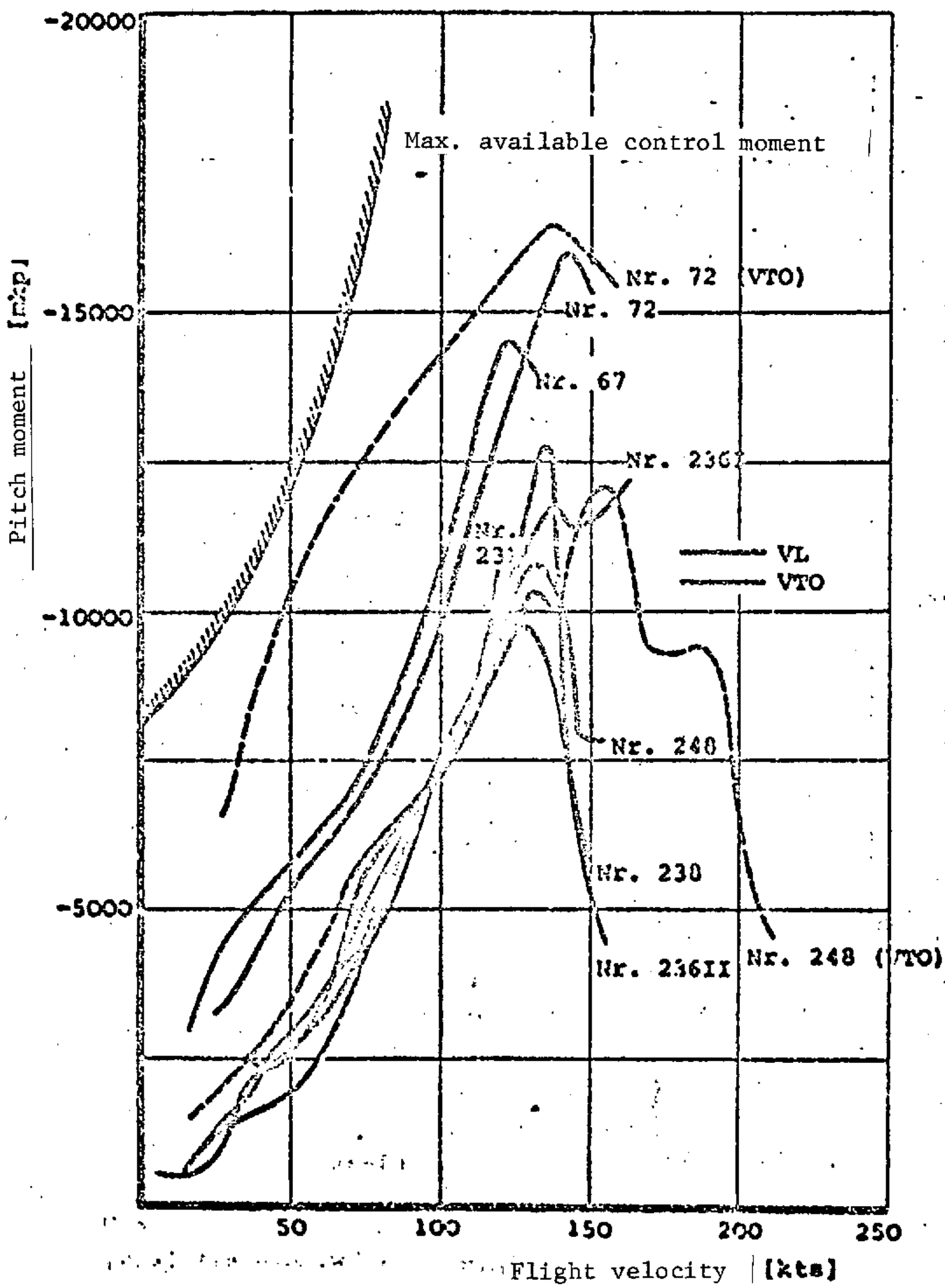


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Figure 12. Variation of the pitch trim moments with flight velocity

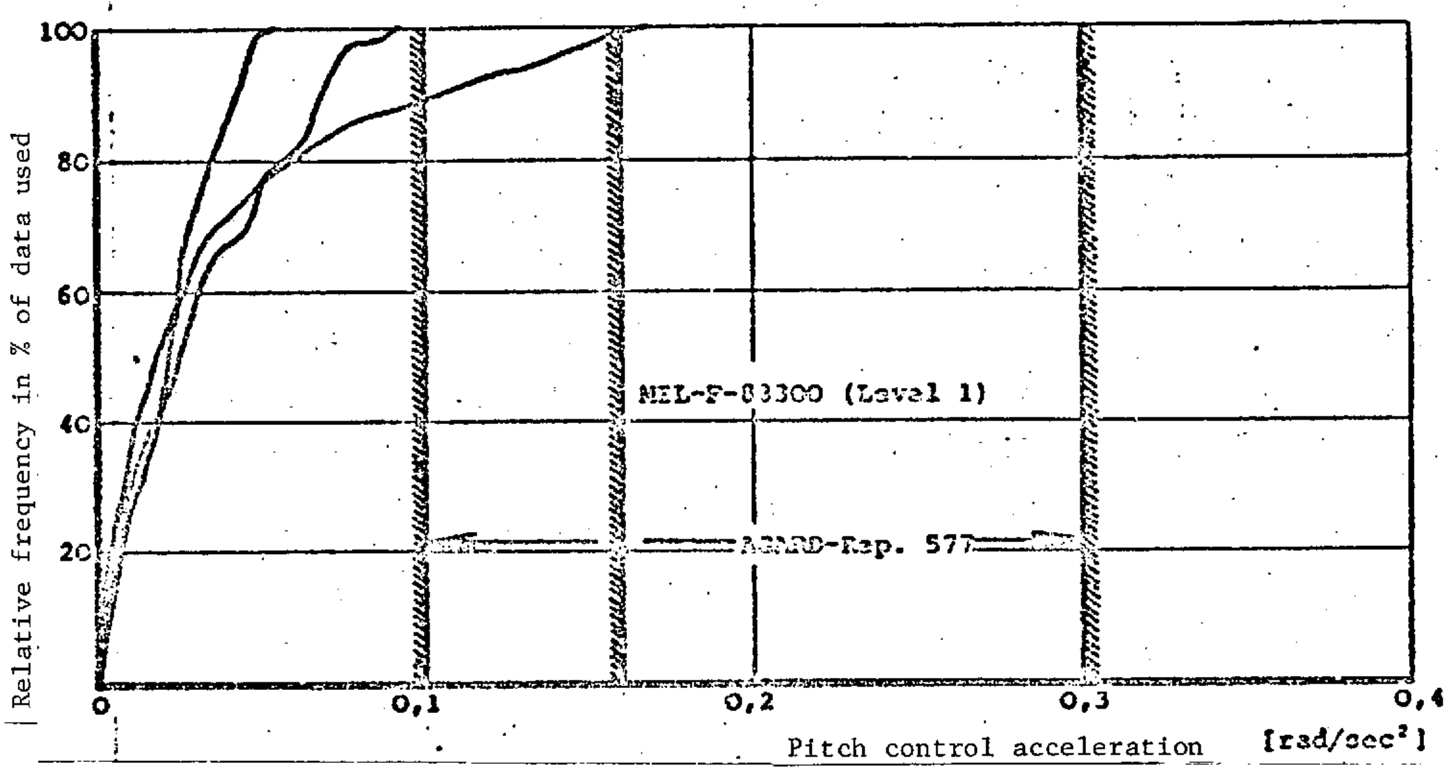


Figure 13. Relative frequency of the pitch control accelerations used compared with the specifications [2] , [3]



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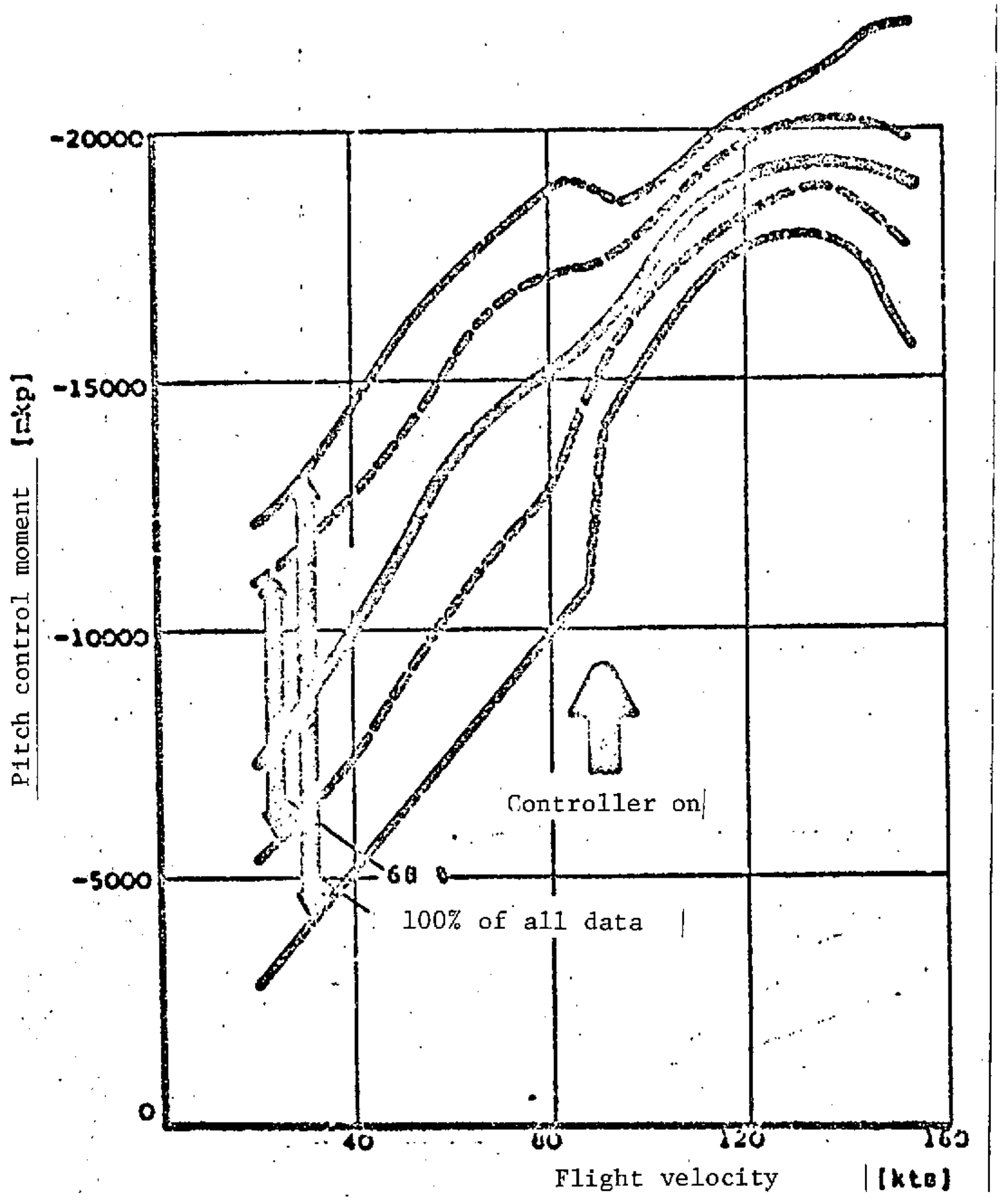


Figure 14. Influence of the attitude stabilization on the control moments used during a typical takeoff transition

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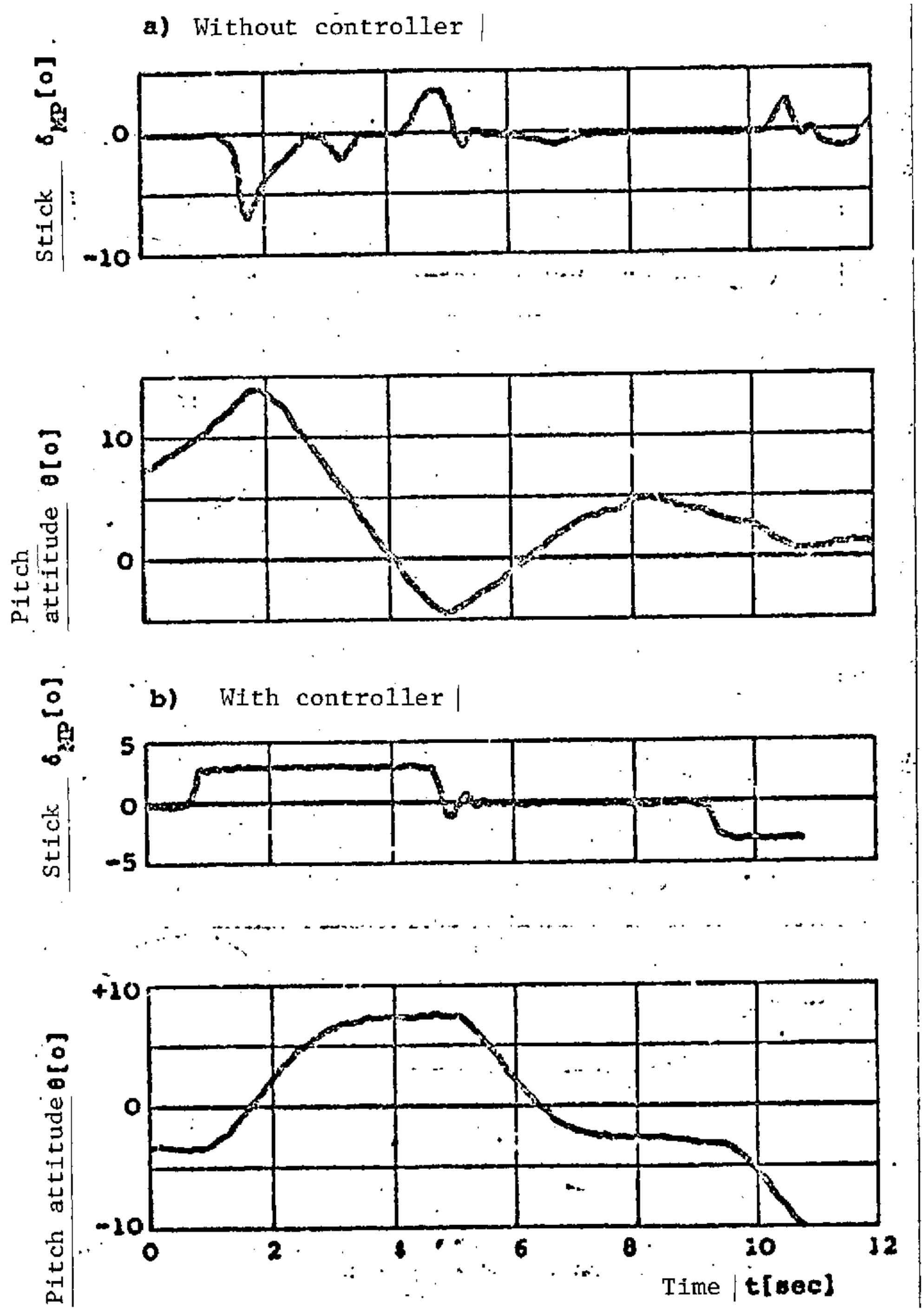


Figure 15. Control of pitch attitude changes with and without controller

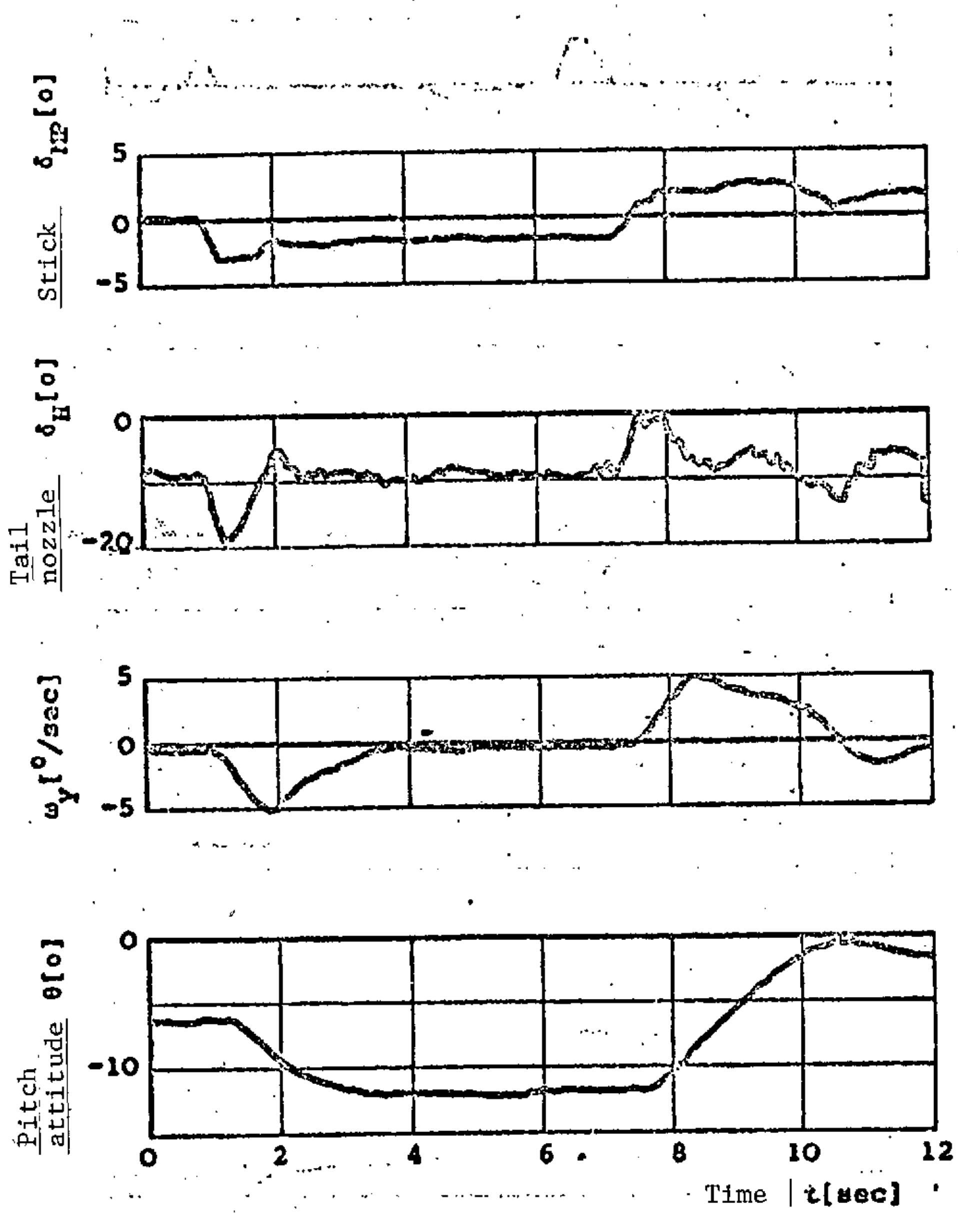


Figure 16. Control of pitch attitude changes with controller during transition at V = 70 kts

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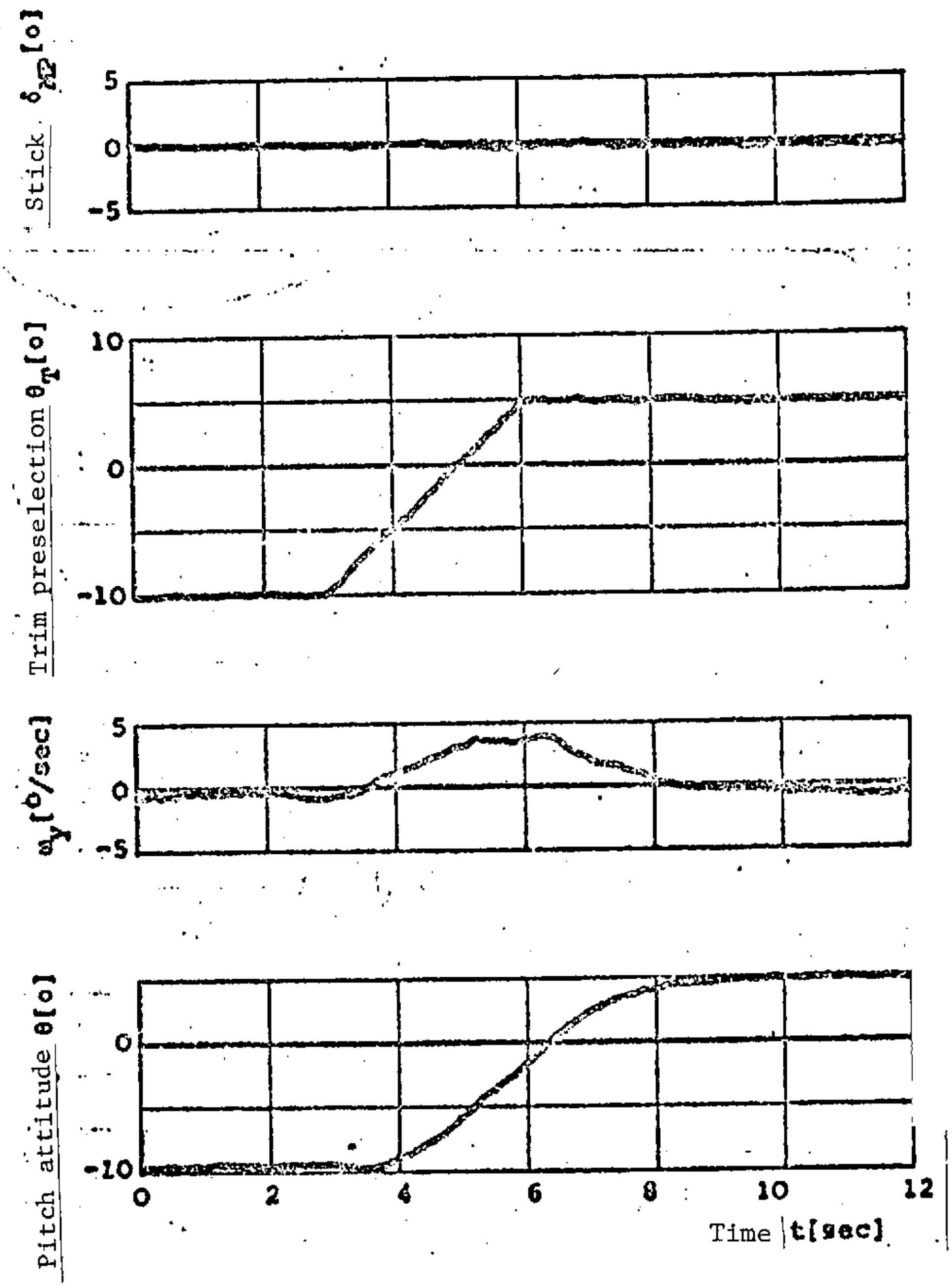


Figure 17. Transient behavior of the pitch attitude when operating the pitch attitude preselection during transition at V = 70 kts

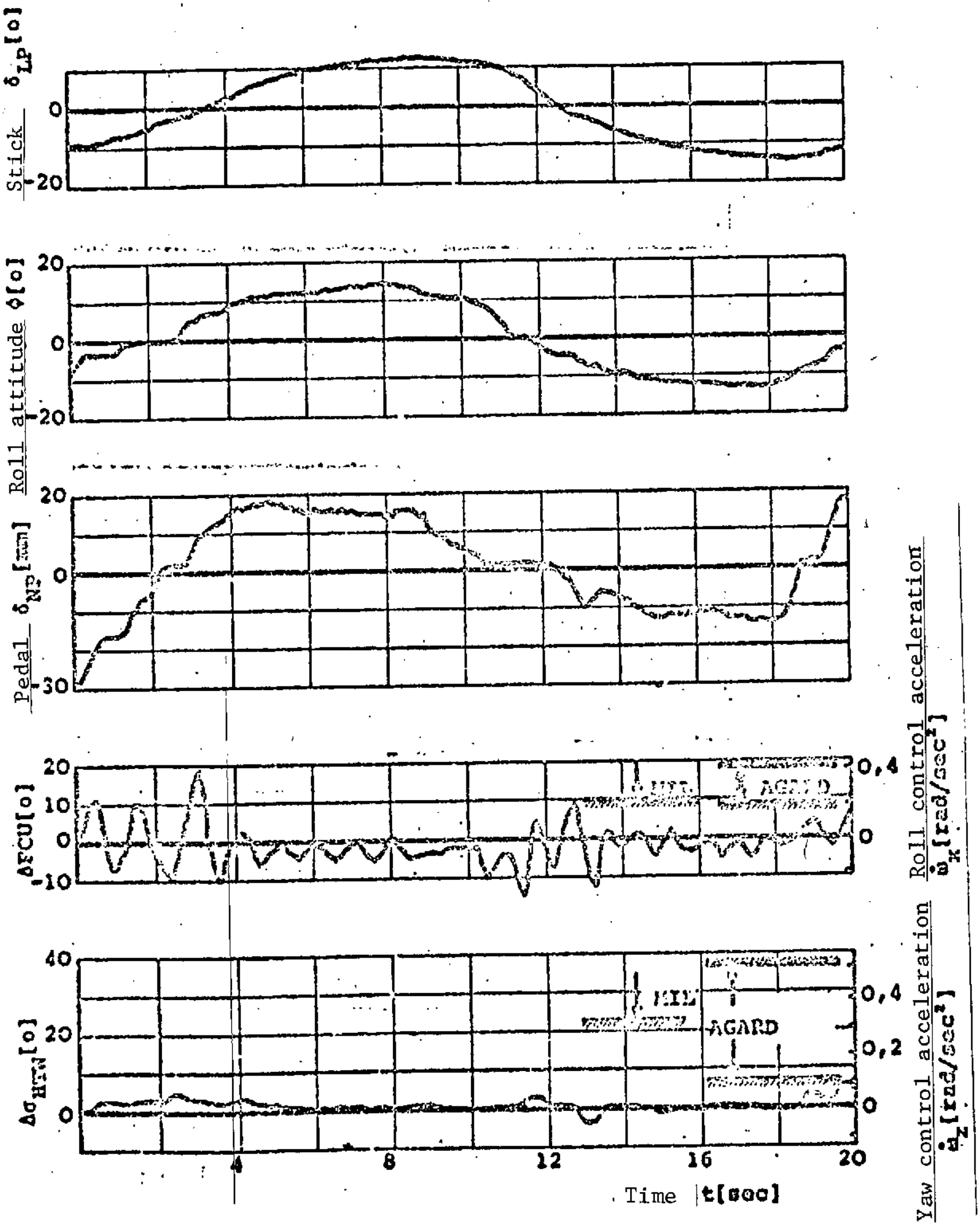


Figure 18. Required roll and yaw control accelerations for controlling a curve change during hovering flight

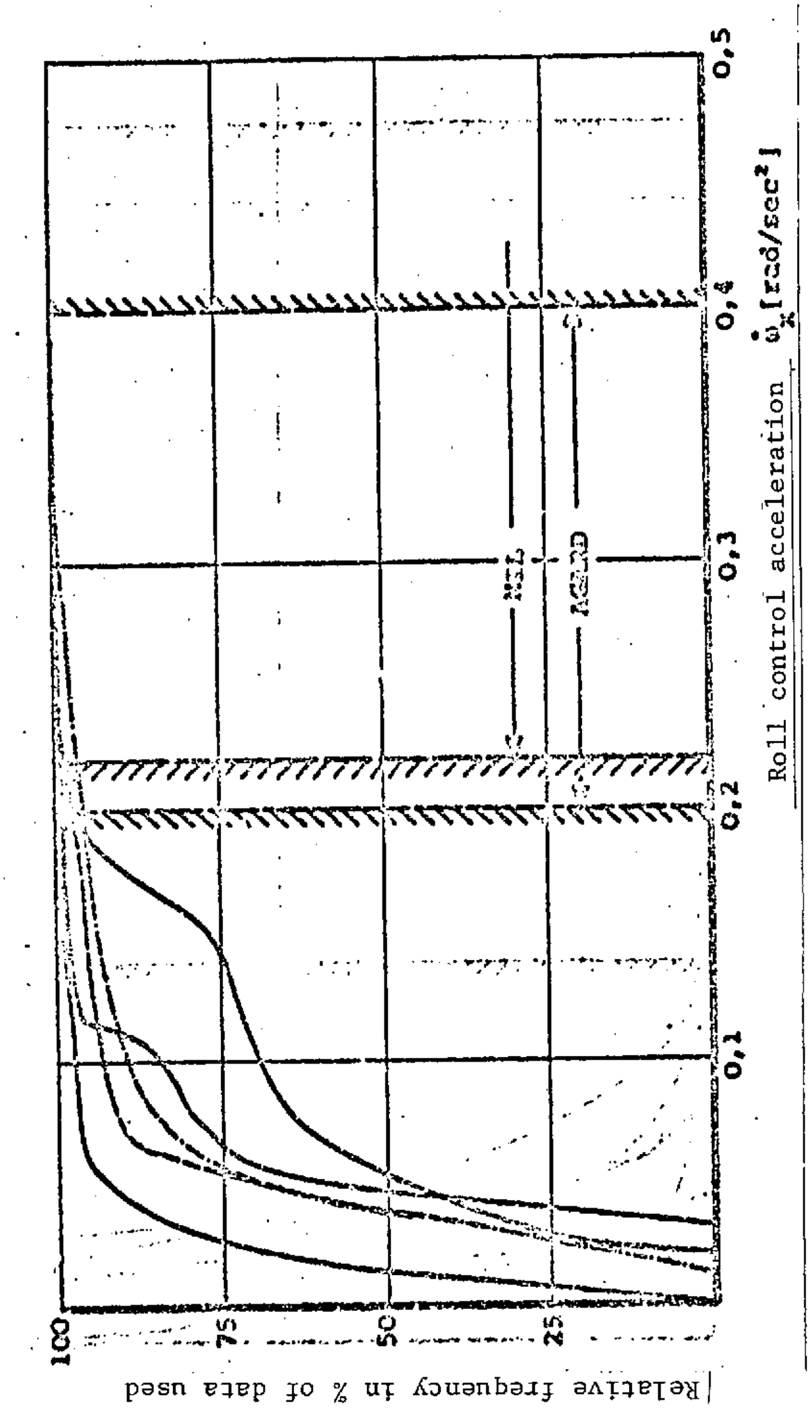


Figure 19. Relative frequency of the evaluated roll control accelerations from hovering flight and transitional flights

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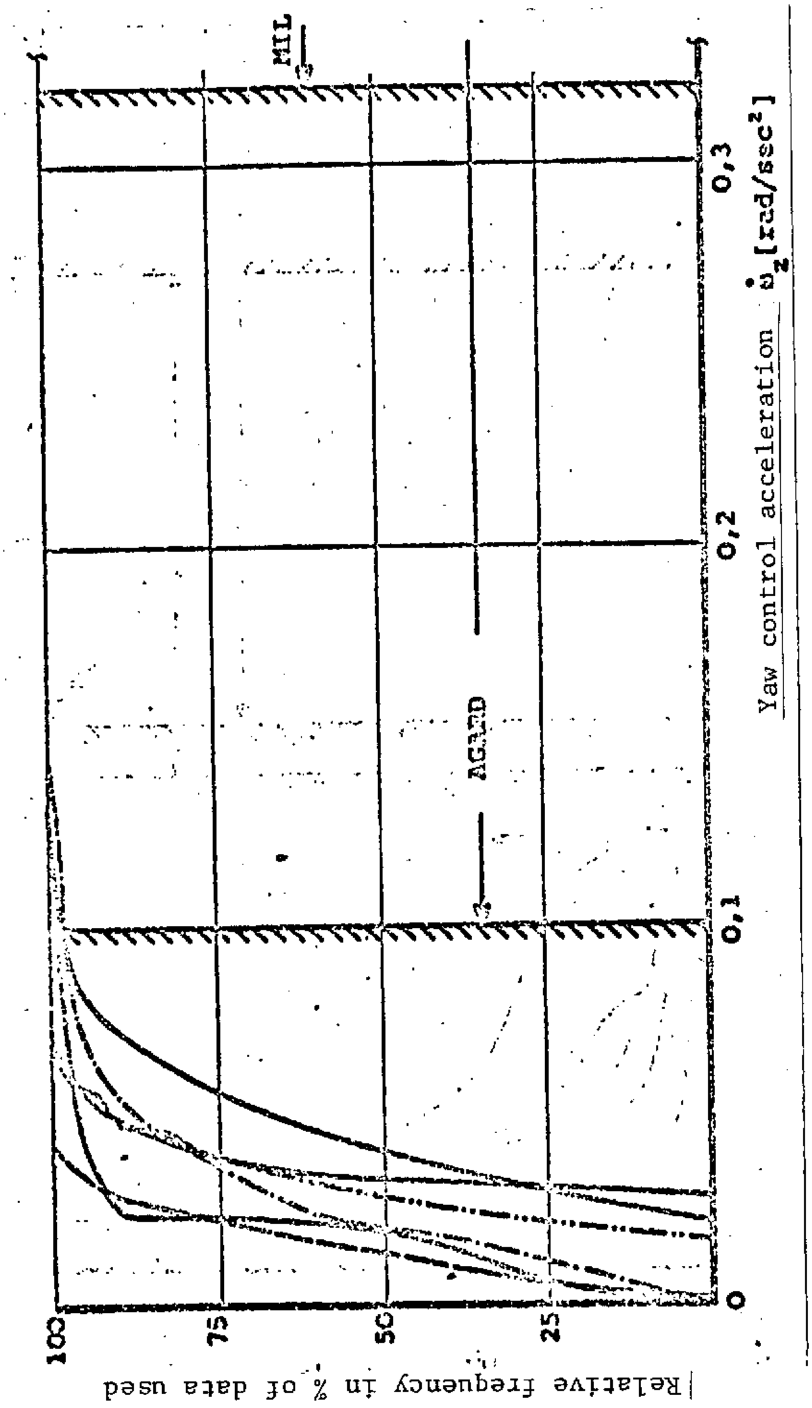
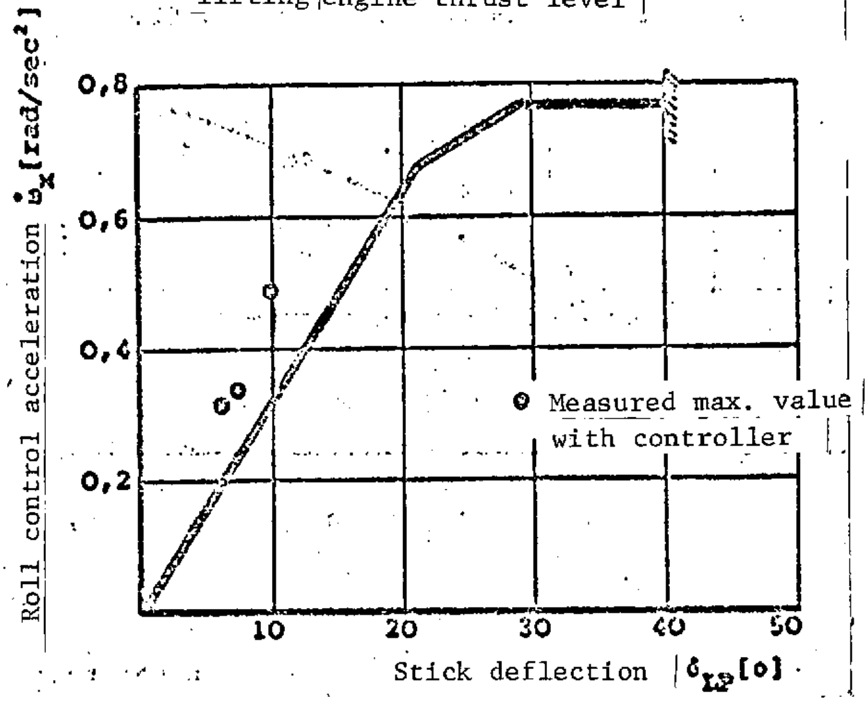



Figure 20. Relative frequency of the evaluated yaw control accelerations from hovering and transitional flights

a) Roll control acceleration for average lifting engine thrust level




b) Yaw control acceleration for average lifting engine thrust level

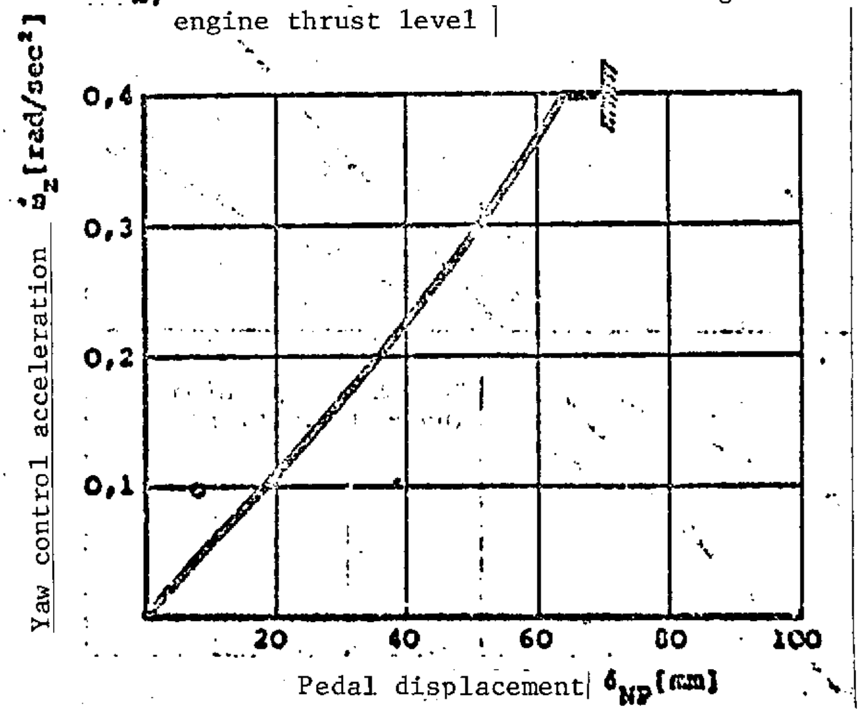



Figure 21. Variation of the roll and yaw control accelerations with control deflection during hovering flight

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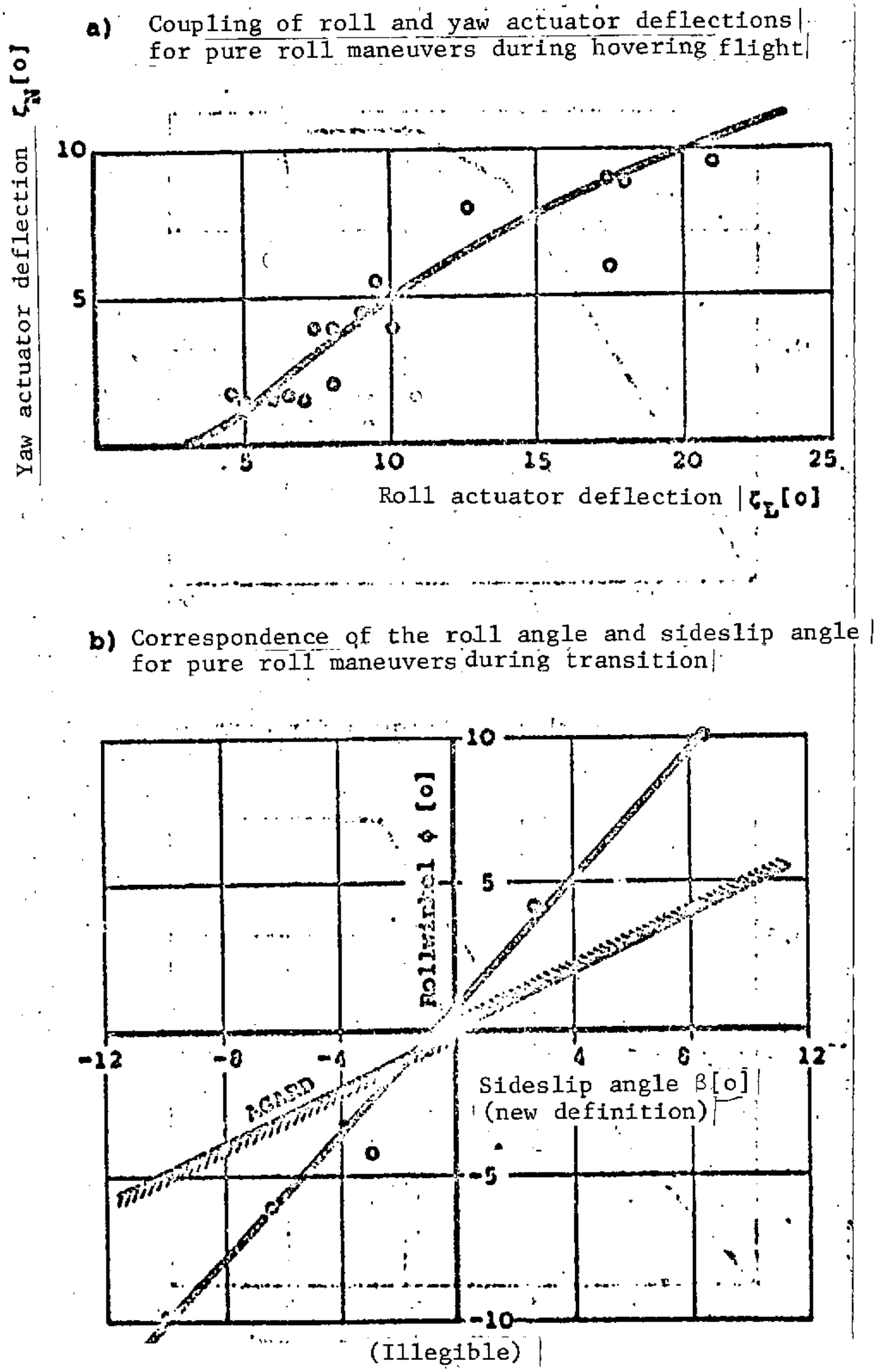


Figure 22. Coupling of roll and yaw axis for roll control inputs during control flight

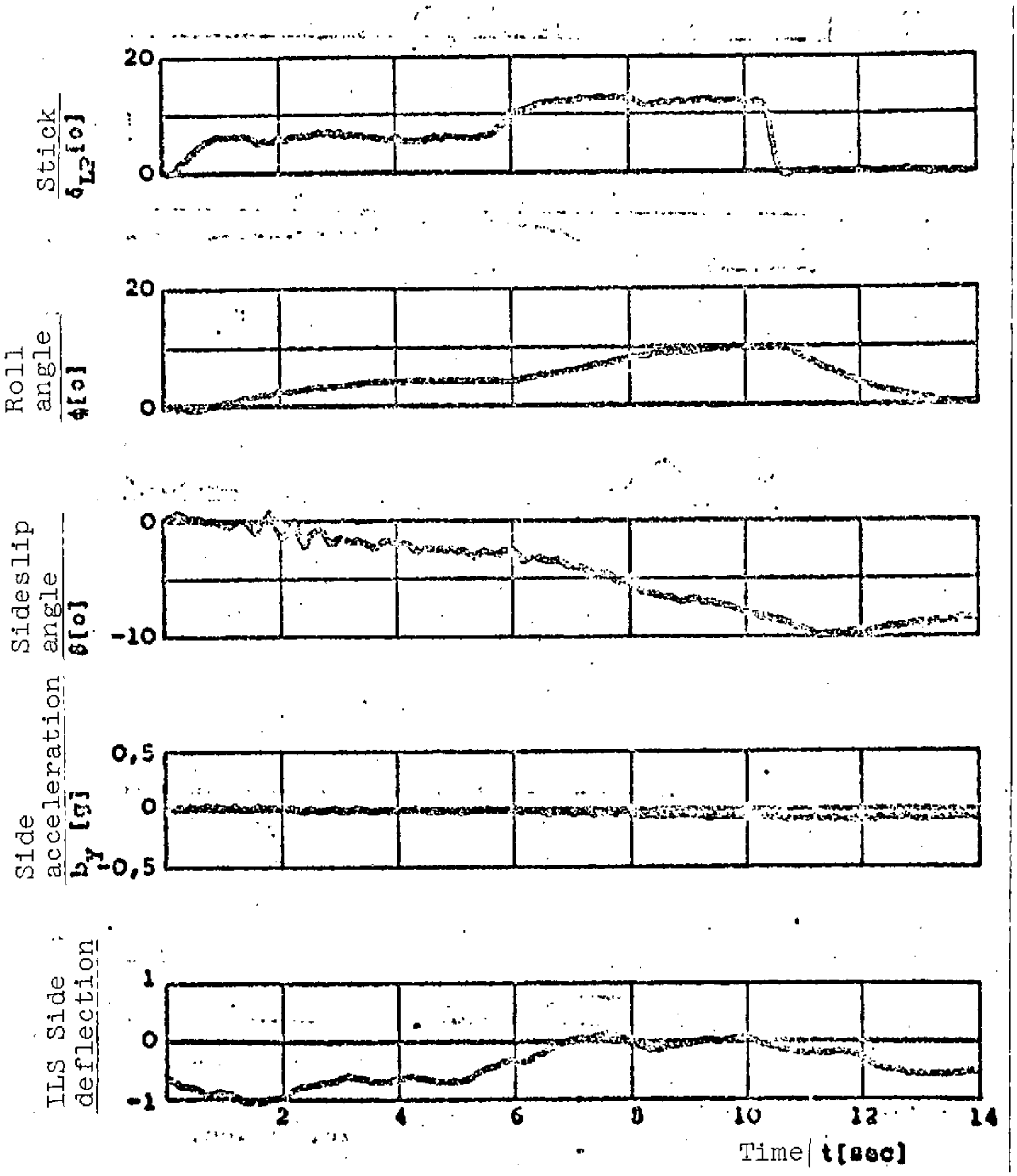


Figure 23. Dynamic side stability at V = 70 kts. Sideways displacement and jump inputs along the roll axis

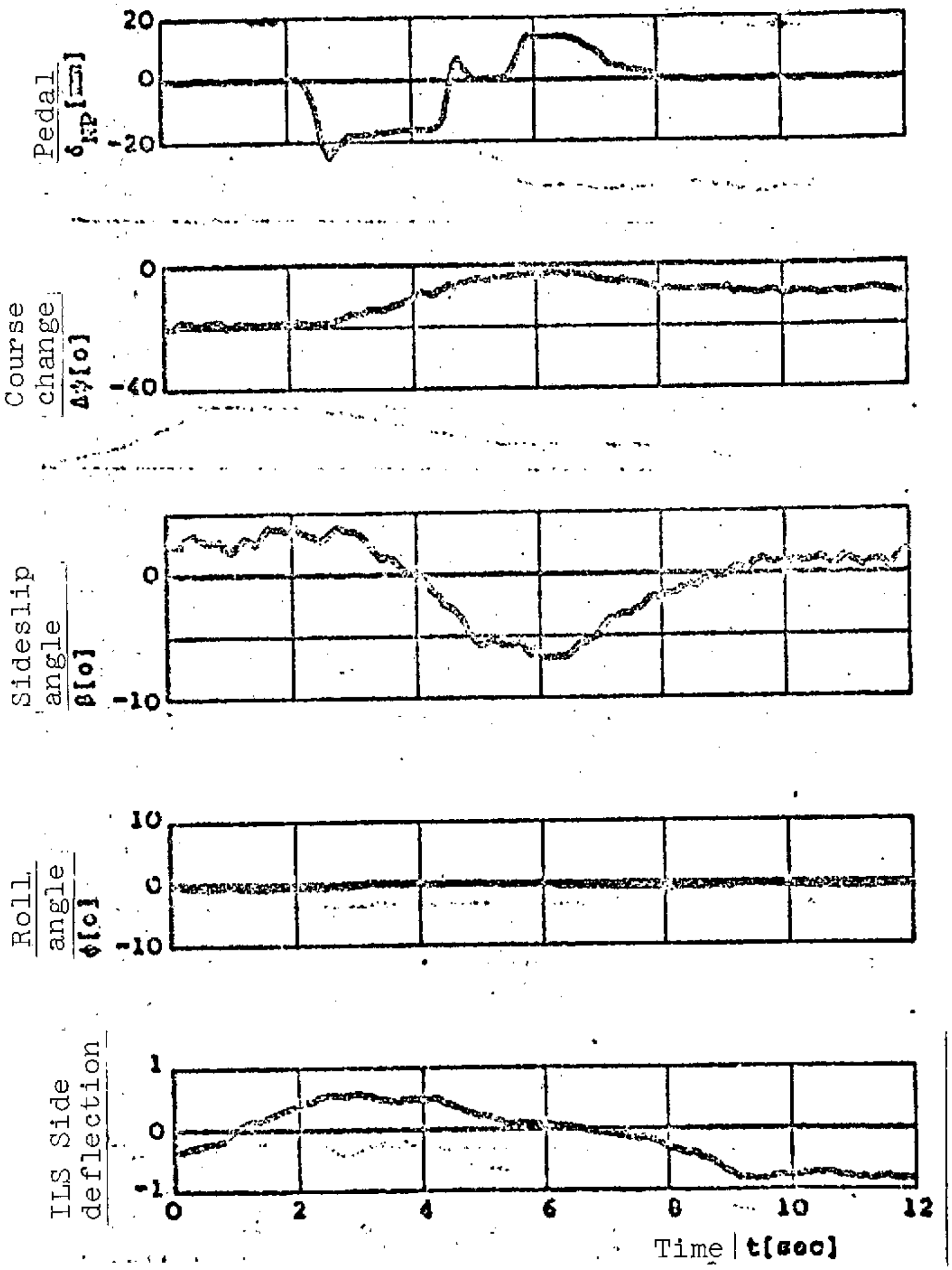


Figure 24. Dynamic side stability at V = 70 kts. Jump inputs to the yaw axis

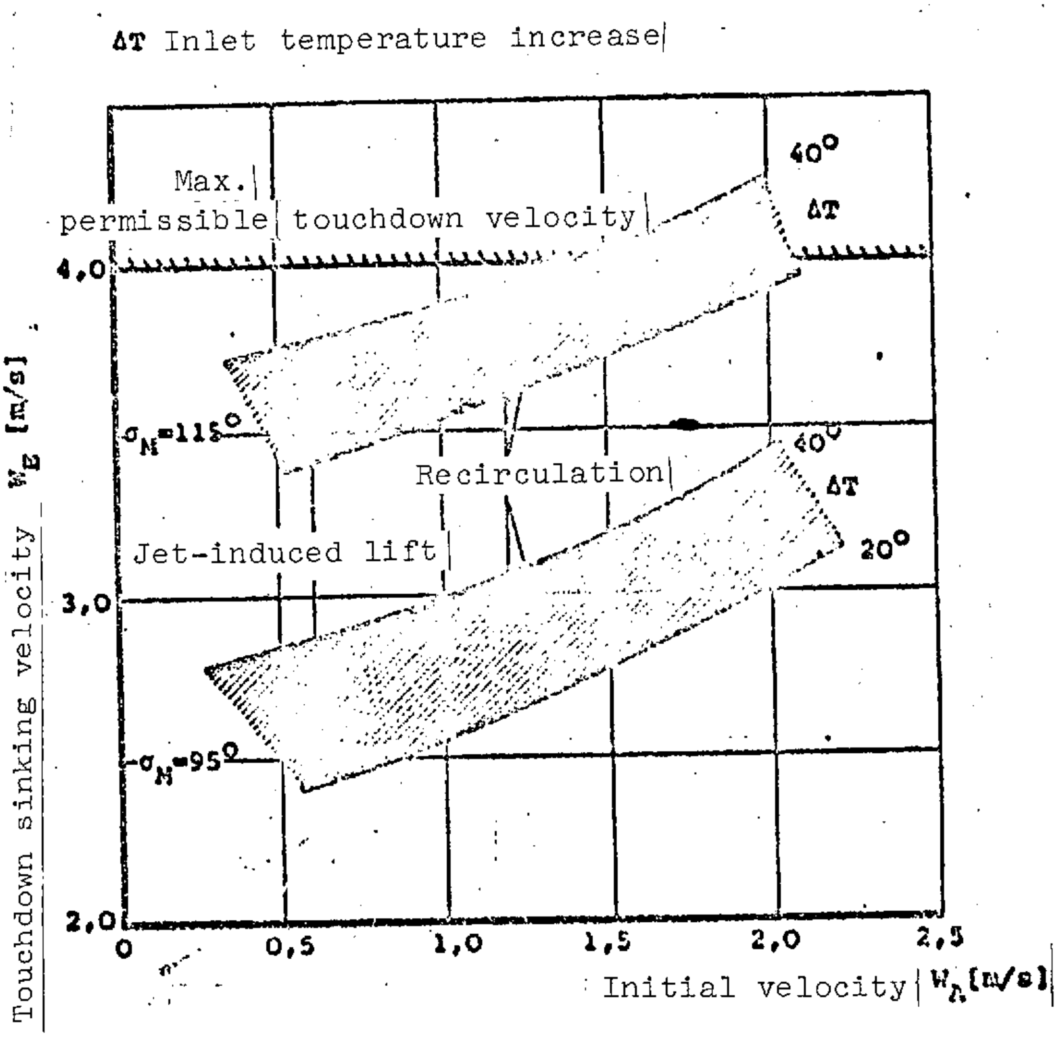


Figure 25. Influence of hot gas recirculation and jet induced downwind on the touchdown velocity for various initial sinking velocities

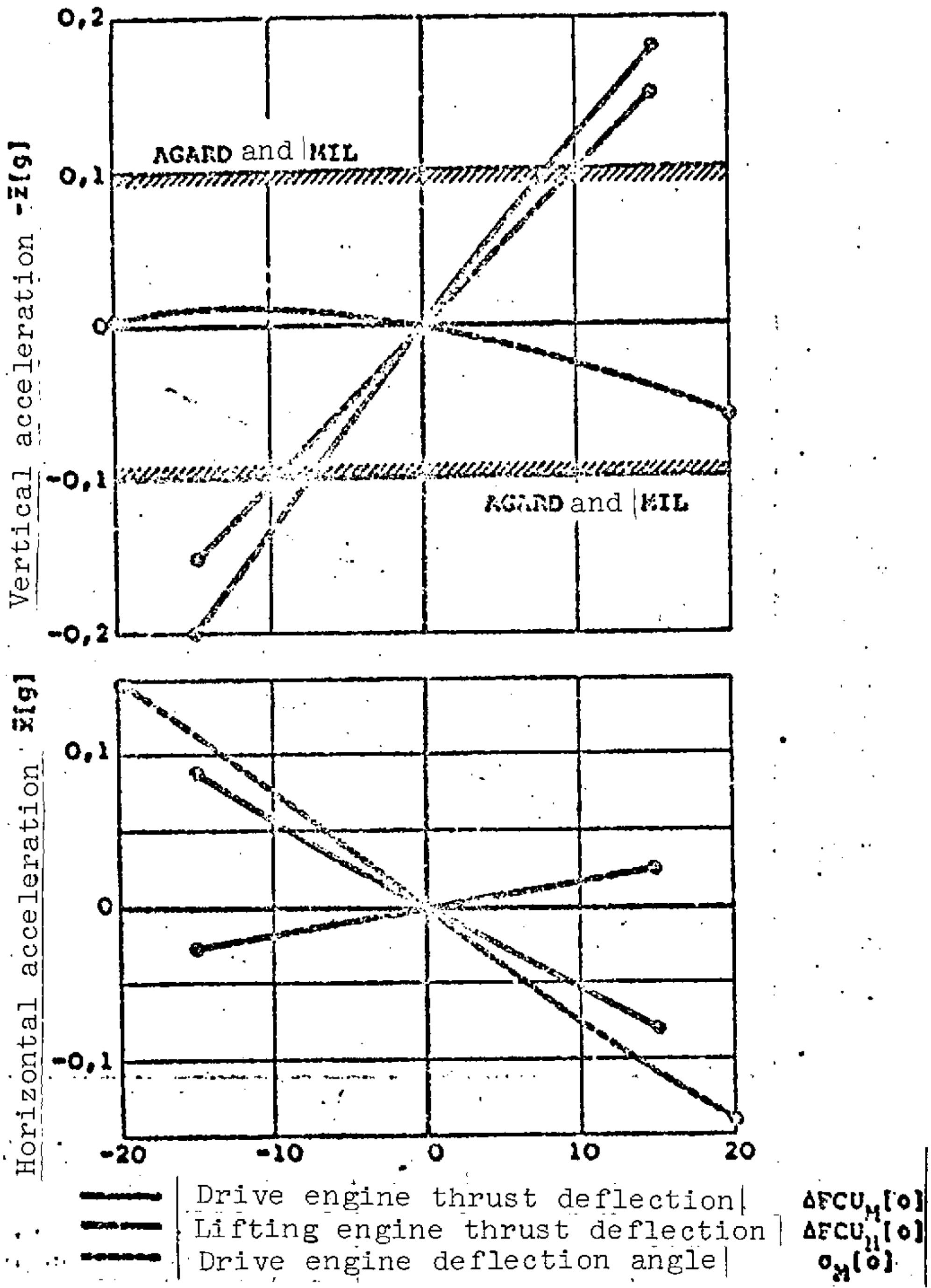


Figure 26. Vertical acceleration capacity for various control measures and related coupling effects for normal variation range during hovering flight

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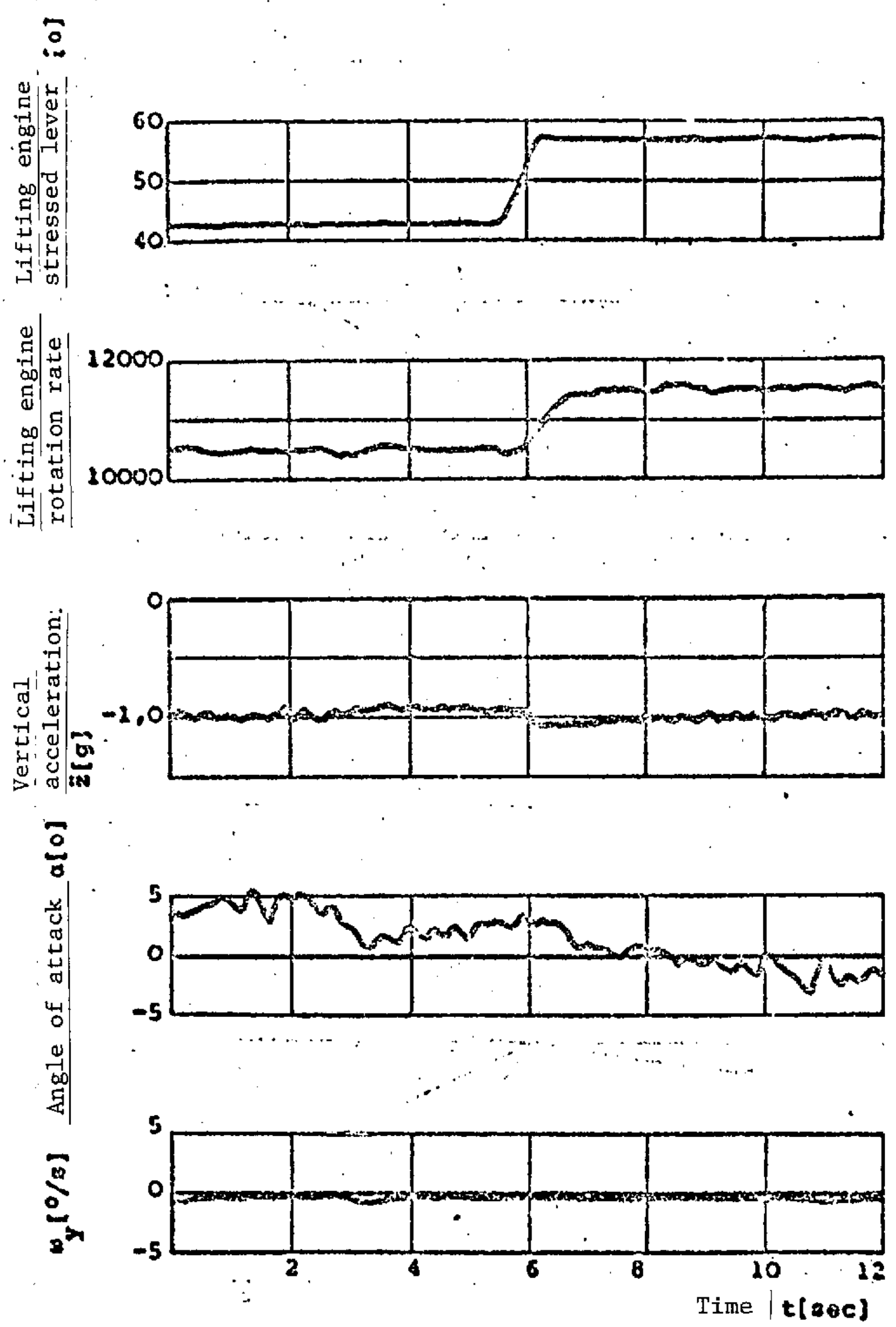


Figure 27. Variation of the vertical acceleration for jump increase of the lifting engine thrust during transition at V = 70 kts

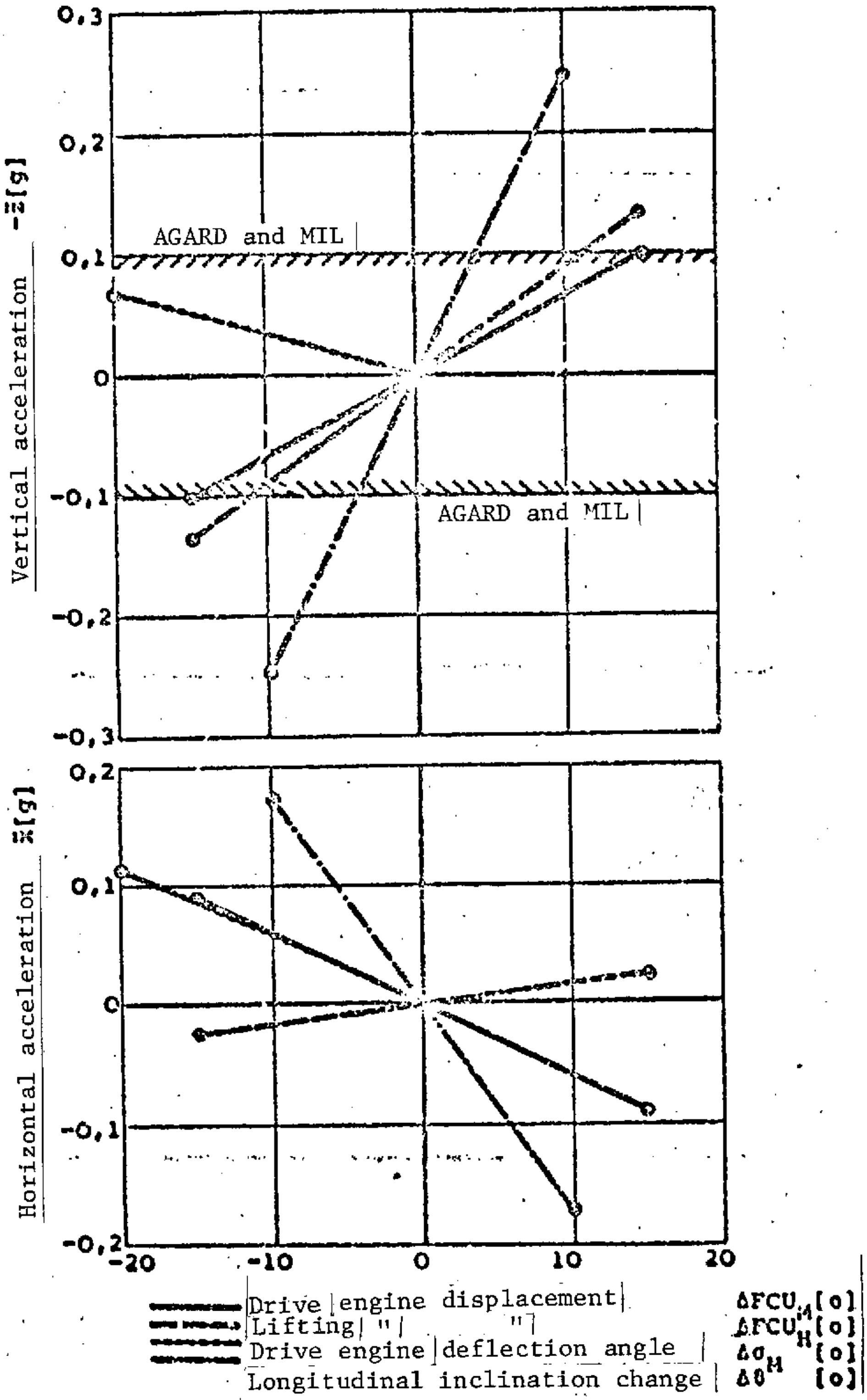


Figure 28. Vertical acceleration capacity for various control measures and related coupling effects during landing transition

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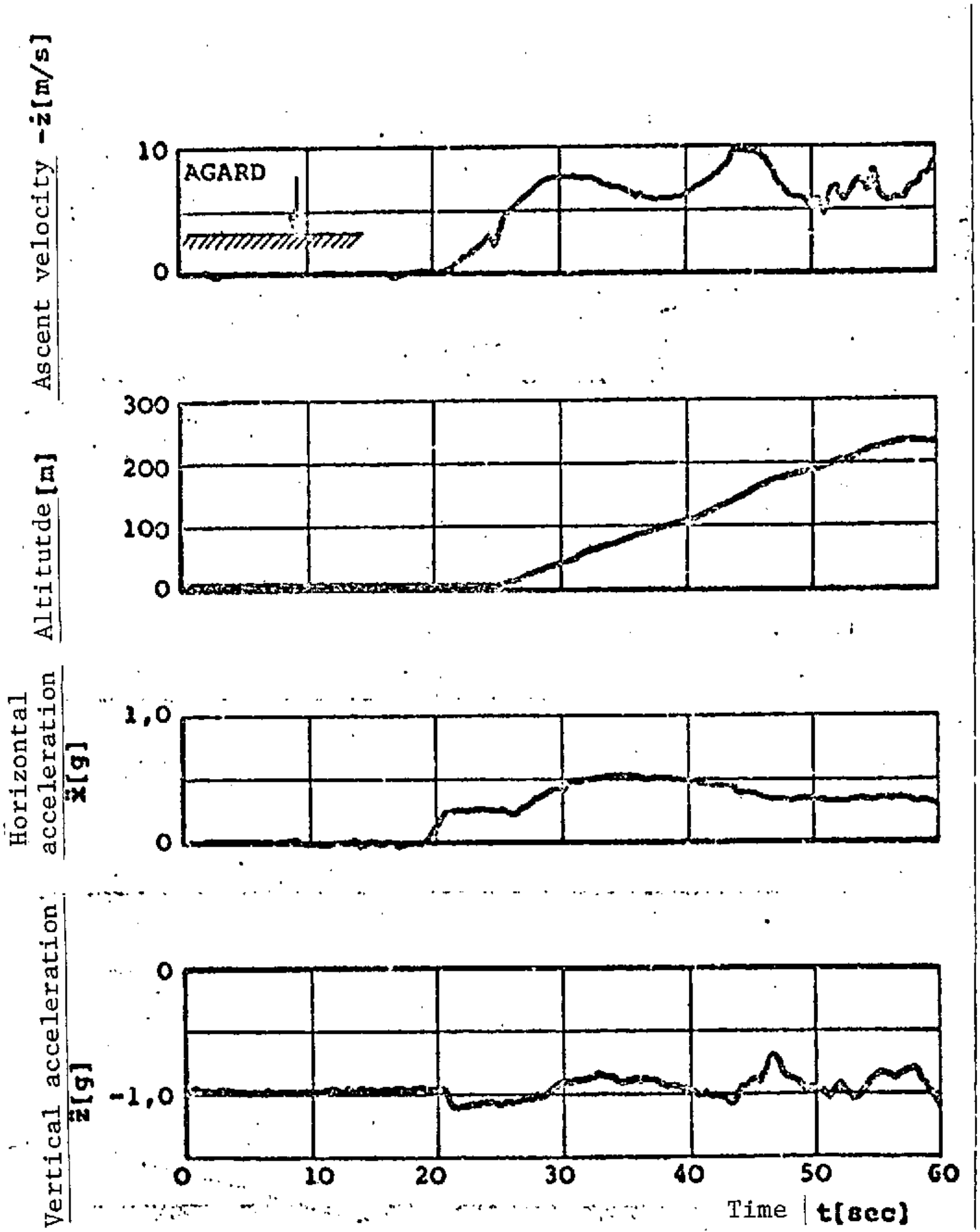


Figure 29. Vertical ascent capacity for vertical takeoff

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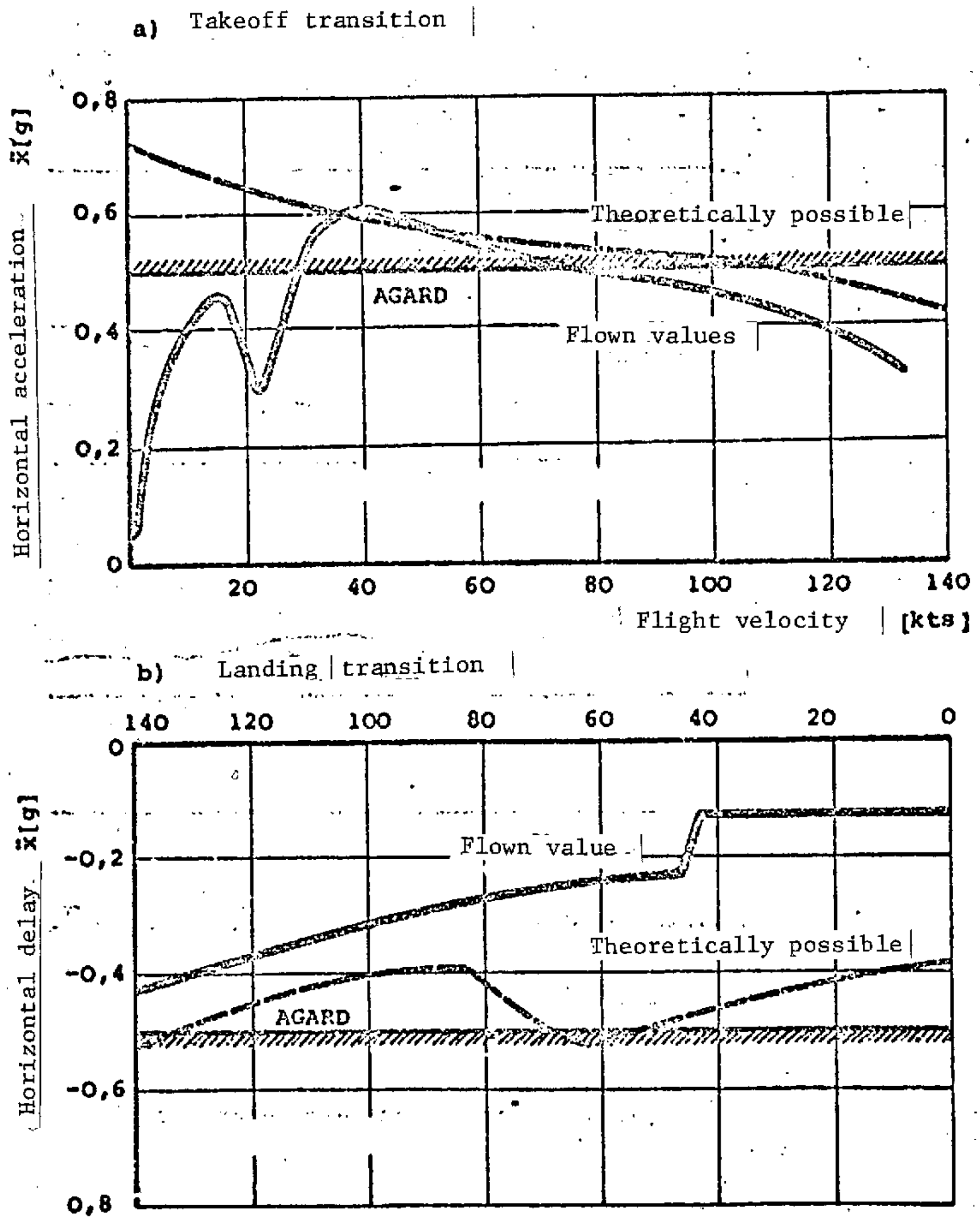


Figure 30. Horizontal acceleration and delay capacity for takeoff and landing transitions

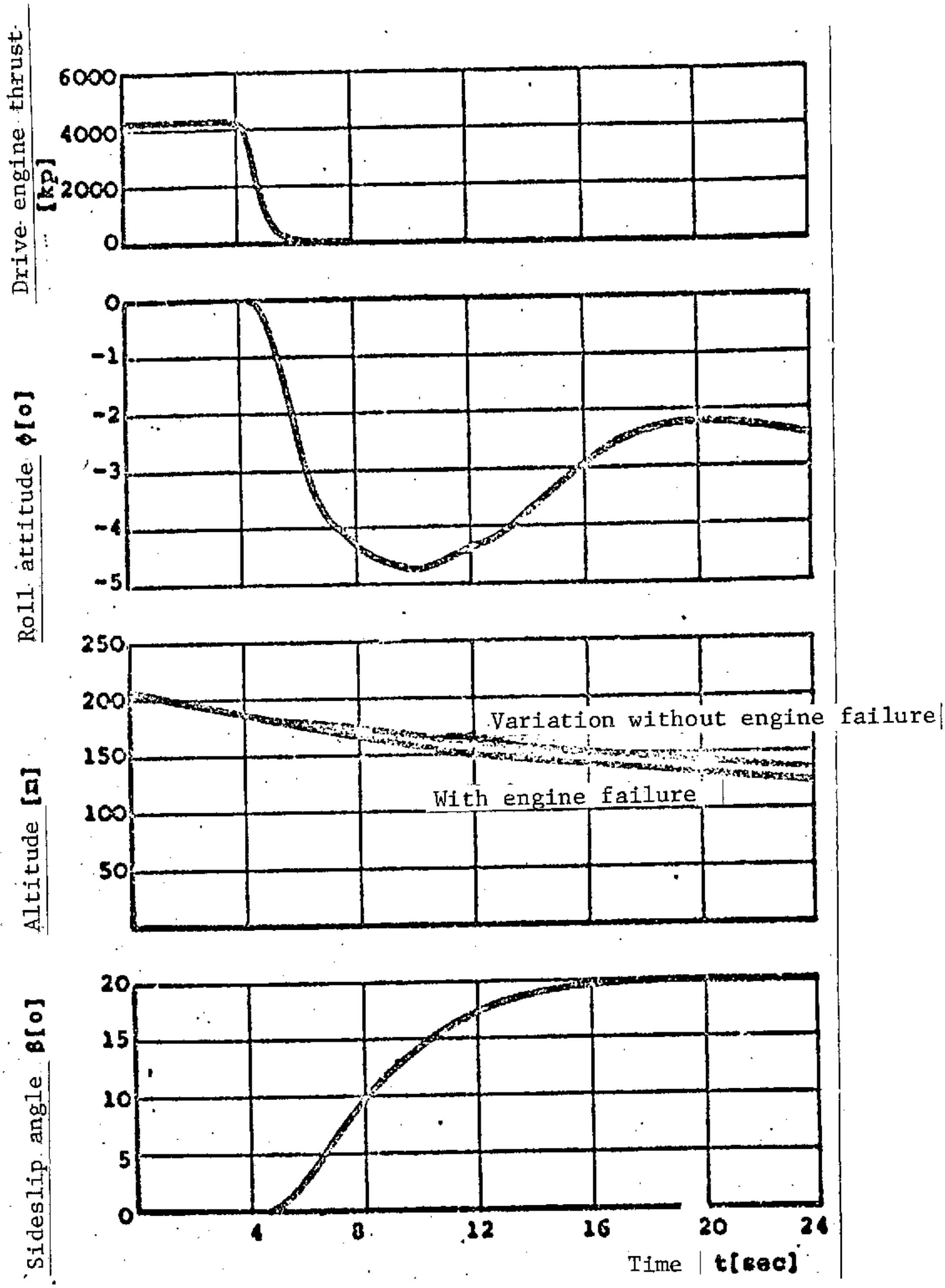


Figure 31. Simulation of a drive engine failure during landing transition.

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STANDARD TITLE PAGE

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15. Supplementary Notes

Translation of "Stabilität und Steuerbarkeit von VSTOL-Flugzeugen nach Verfahren und Ergebnissen aus der Do 31-Flugerprobung", Dornier-Werke G.m.b.H., Friedrichshafen, (W.Ger.), BMVg-FBWT-72-25; 1972, 90 pp.

16. Abstract

The problems of stability and control of V/STOL aircraft are discussed. Though the V/STOL handling qualities criteria in AGARD-Rep 577 and US-MIL-F-83300 correspond to a certain extent to the flight test results of the Do 31, the MIL Spec. in particular is not applicable to jet lift V/STOL aircraft with attitude stabilization systems. As far as AGARD Rep. 577 is concerned, additional information seems to be necessary in order to include the special problems of this category of V/STOL aircraft. The principles of control and stabilization used for the Do 31 have proved its validity and have even enabled the pilots to perform simulated IFR transitions up to hovering flight. However, for an operational aircraft, improvements to simplify handling and further automation of the landing approach are essentially necessary for all weather operations.

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